The geological environment of post-caledonian base-metal mineralization in Ireland

Russell, Michael John

Plate 1

Comparative sections in the Dinantian rocks of Ireland. The number of samples collected from particular lithologies or zones are recorded on the right hand side of the columns.

Sulphide mineralization is shown in green.

Section 1 : Varvill 1959

Section 2 : Padget 1951; Sheridan, Hubbard and Olroyd 1967

Section 3 : Caldwell 1959

Section 4 : Patterson (pers. comm. 1968)

Section 5 : Smyth 1915; 1939; 1950; Hudson, Clarke and Sevastopulo 1966; Mamet 1969

Section 6 : Schultz 1966a

Section 7 : Douglas 1909; Hallof, Schultz and Bell 1962; Schultz and Sevastopulo 1965; Hudson and Sevastopulo 1966

Section 8 : Rhoden 1958; Weber 1964

Section 9 : Shephard-Thorn 1963

Section 10: Ashby 1939

Section 11: Thompson 1967

Section 12: Cameron and Romer 1970

Section 13: Hudson, Clarke and Brennand 1966

Section 14: Smyth 1930; 1939; Hudson, Clarke and Brennand 1966

THE GEOLOGICAL ENVIRONMENT OF POST-CALEDONIAN BASE-METAL MINERALIZATION IN IRELAND

by

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A thesis submitted for the degree of Doctor of Philosophy (PhD)
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PUBLICATIONS

RUSSELL, MJ 1968

Structural controls of base metal mineralization in Ireland in relation to continental drift.
Trans. Instn Min. Metall. 77 B, 117-28

RUSSELL, MJ 1969

Discussions and contributions:
Structural controls of base metal mineralization in Ireland in relation to continental drift.
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North-south geofractures in Scotland and Ireland.
Scott. J. Geol. 8, 75-84

See inside rear pocket

ABSTRACT

The Dinantian host and wall rocks to the Ballyvergin, Gortdrum, Oola, Carrickittle and Tynagh base-metal deposits were analysed for a variety of trace elements with a view to establishing a local sedimentary syngenetic contribution of metals. Against expectation all the trace element aureoles examined proved the epigenetic nature of the sulphide mineralization. The aureoles are of two kinds corresponding to the sulphide deposit types. The copper deposits in the Lower Limestone Shales and the argillaceous Lower Limestones; Ballyvergin, Gortdrum and Oola, are fringed with enrichments of arsenic and lead, whereas the Waulsortian wall rocks to the Tynagh and Carrickittle lead-zinc deposits contain uneven enrichments of many trace elements. A reconnaissance survey in the Waulsortian mud bank complex to the westnorthwest of Tynagh revealed what may be an extensive syngenetic manganese aureole to the Tynagh chert-hematite deposit. The exhalative origin proposed by Derry, Clark and Gillatt (1965) for the Tynagh iron deposit is supported by chemical analysis. Thus hot springs were in existence at Tynagh in mid-Dinantian times. This was probably the case too at Silvermines (Graham 1970). The iron deposit at Keel as well as the thick developments of chert at Silvermines and Aherlow are taken here as additional evidence for a mid-Dinantian age for the onset of mineralization.

Although the local structural controls to the sulphide deposits may be related to the Armorican Orogeny, the distribution of the ore deposits is more easily explained in terms of north-south geofracturing caused by the tensile stresses which eventually led to the formation of the Atlantic (Rockall Trough) margin. The recent discovery of the Navan sulphide deposit was broadly predictable by this theory.

I INTRODUCTION

Aims and Motivation

This thesis is about the geological environment of base-metal deposits recently discovered in Dinantian rocks in Ireland. The research was prompted by the desire to test the syngenetic model put forward by some exploration geologists as an explanation of these sulphide deposits (Pereira 1963).

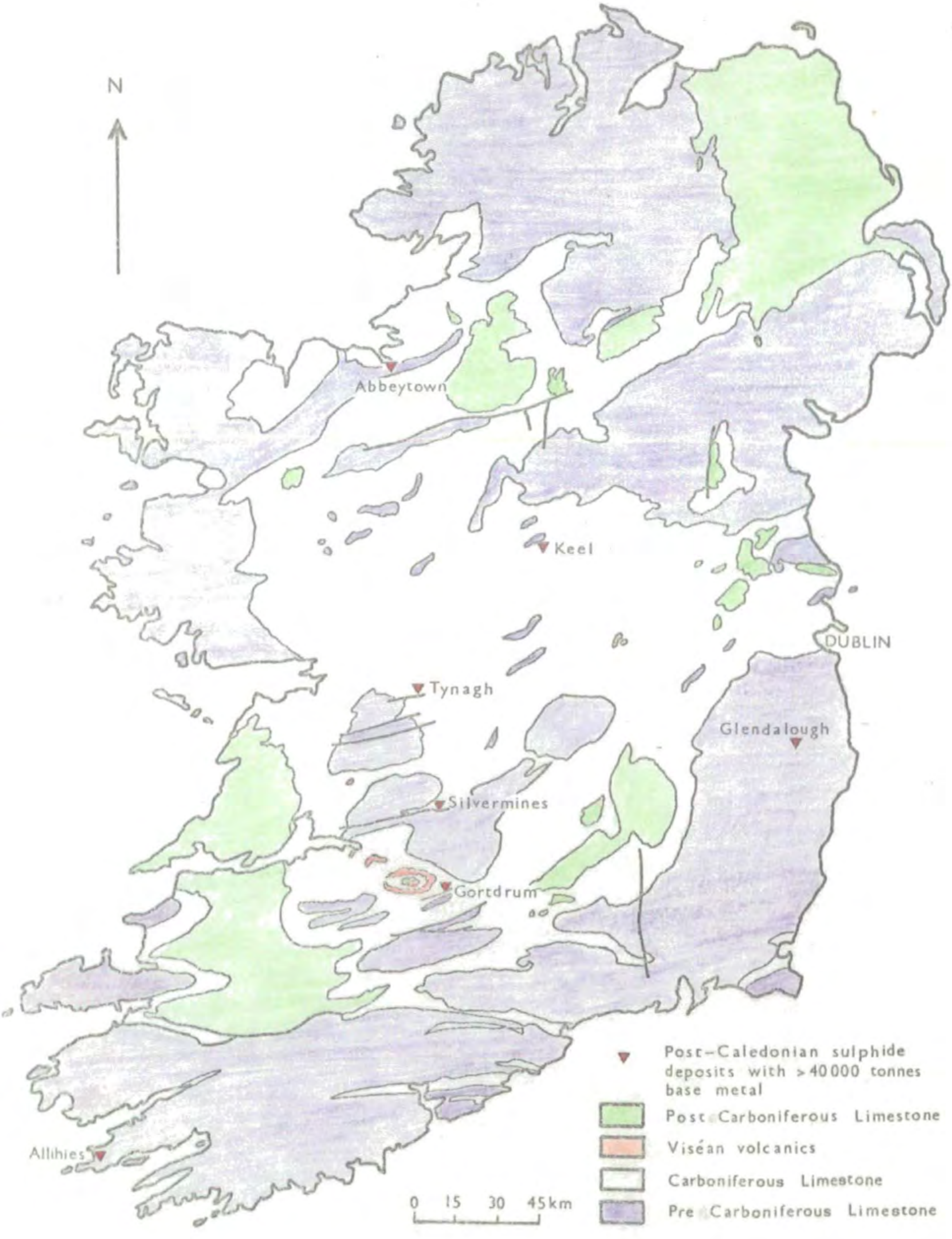
Location

Since 1961 several large sulphide deposits have been discovered in Ireland (Figure 1 - 1). A reconnaissance investigation was made of the trace element concentrations in host rocks to four of these discoveries; the Tynagh and Gortdrum ore bodies, and the two smaller deposits of Ballyvergin and Carrickittle. Background samples from Dinantian sections were taken from coastal exposures in east, south and west Ireland, and likewise analysed for trace elements.

Previous Investigations

The first accounts of Irish sulphide deposits are those of the "Neptunist" Weaver, (1819; 1838), who described veins at Silvermines and irregular sulphide deposits in County Kerry in terms of contemporaneous deposition and segregation. Under the same influence, John Taylor (1830, in Weaver) considered the then newly discovered lead deposits in County Clare (Ballyhicky, Killbricken and Milltown) as 'erect contemporaneous masses in the limestone rock'. In 1922 Cole compiled a list of old mineral showings in a memoir describing the modes of occurrence of the ores in terms of veins, lodes, layers, stringers and disseminations.

Further information on the Silvermines mineralization was afforded from cores drilled by the Silvermines Lead and Zinc Company between



N
Abbeytown
Keel
DUBLIN
Tynagh
Glendalough
Silvermines
Gortdrum
Allihies
0 15 30 45km
Post–Caledonian sulphide deposits with >40 000 tonnes base metal
Post Carboniferous Limestone
Viséan volcanics
Carboniferous Limestone
Pre Carboniferous Limestone

Figure 1 - 1

Simplified geological map of Ireland copied from the Geological Survey of Ireland 1:750,000 geological map 3rd edn 1962). The important post-Caledonian base-metal deposits known to be present in Ireland at the beginning of this research are shown. (Glendalough could be a late Caledonian deposit but as there is no evidence regarding its age it is included here).

1952 and 1957. Here, several old mines occurred near the east-west trending Main Fault (Figure 7 - 1). Rhoden (1958) described the mineralization in detail and concluded that 'epigenetic material ascended through the fracture system .... and dispersed .... into favourable Upper Palaeozoic formations. Mineralization was later than post-Carboniferous folding and faulting .... and .... may be of Triassic to early Jurassic age.'. According to this work, all major deposits are centered on the Silvermines Fault, however several veins occur in the Lower Palaeozoic rocks to the south. A marked contrast in colour between the red and buff Old Red Sandstone beds on Keeper Mountain and the light grey sandstones and olive green shales on Silvermines Mountain is due to the sulphidation of sedimentary iron oxides (Rhoden 1958).

In the following year, MV O'Brien (1959) remarked some copper stained sandstone boulders derived from an east-west fault line which juxtaposed an Old Red Sandstone inlier with Carboniferous Limestone at Tynagh in County Galway. Reviewing mineral occurrences in the Lower Carboniferous rocks, O'Brien mentioned Silvermines, East Clare, County Kerry and paid especial attention to the Abbeytown zinc-lead deposit, attributing the latter's seven years of production up to 1958 to a systematic diamond drilling campaign. In the same paper mineralization along an east-west fault at Oola is also mentioned and some veins in the Silurian rocks a few miles north of Oola were considered as possible roots of similar mineralization. O'Brien described the deposits in the Dinantian rocks as being nonconformable replacement bodies.

MV O'Brien, then Director of the Irish Geological Survey, recommended the Tynagh area, amongst others, to PJ Hughes who had returned from Canada to Ireland to prospect for ore deposits. The fact that the fault at Tynagh was of a similar orientation and character to that at Silvermines was an additional attraction. A geochemical survey of the area culminated in the discovery of the Tynagh base-metal mine in late 1961.

The next publication on mineralization in Ireland was on a newly discovered dome shaped deposit of disseminated chalcopyrite in the east Clare area at Ballyvergin. Hallof, Schultz and Bell (1962) tentatively considered that the mineralization was derived from ascending hydrothermal solutions and deposited in a pre-ore fold as replacement and fracture fillings.

At about the same time, the Rio Tinto Zinc Corporation made a geochemical investigation of the Longford-Carrickboy area. This was followed by an induced polarization survey at a limestone-sandstone contact, which in turn led to the drilling of a zinc-lead body in Dinantian and possible Old Red Sandstone rocks just to the south of a Lower Palaeozoic inlier at Keel. The area was one of a number selected by the Rio Tinto Zinc Corporation on the basis of a belief that the factors causing primary mineralization were multiple, and that sedimentary controls were important amongst these (pers.comm. Bowler 1971). An exposition of this thinking followed (Pereira 1963). In this hypothesis, sulphide bodies in Ireland were classified as post-orogenic coastal deposits. The mineralizing solutions arose from submarine fumaroles, and the metals were precipitated in back reef facies or lagoons possibly aided by bacterial activity. Major fissures originating in the mantle were thought to be one of the principal regional controls that governed the distribution of mineral provinces (Pereira 1963).

The Tynagh discovery inevitably led to a review of the old mining areas and in 1963 Consolidated Mogul began drilling at Silvermines, north of Knockanroe, and in the Gorteenadiha Townland. Rhoden (1958) had made certain recommendations for future exploration in his paper on the Silvermines district. These suggestions were based on extrapolations from an idealised section across the Silvermines Fault and were grounded in an epigenetic theory. Accordingly the best prospects for untapped ore zones were considered to be close to the Main Fault, and notably as disseminations in down-faulted

Carboniferous rocks further north of the faults in Gorteenadiha Townland (see Figure 7 - 1). The Ballynoe baryte deposit, lying almost 300 m north of the Main Fault was categorized as a replacement deposit, this type of mineralization having spread north while the ores richest in copper, zinc and lead were being concentrated near the Main Fault. The drilling produced only marginal, and narrow widths of, mineralization and curtailment of the project seemed warranted. However, Weber (pers. comm. 1966), Consolidated Mogul's geological consultant, believed the area to be similar to the Meggen pyrite-sphalerite-barite deposit in Germany, long considered a syngenetic deposit (Schmidt 1918, in Dunham 1964), and suggested investigating north of the Main Fault. Drilling in this area encountered what is now known as the Upper Zone of the 'G' orebody. This success prompted an intensive drilling programme, totalling 280 holes by July 1964, which outlined, in addition to the extensive 'G' Upper Zone zinc-lead deposit, a small Lower Zone of lead-zinc as well as the 'B' zinc-lead deposit. In a short paper in 1964 Weber considered the Upper Zone sulphides (which accounted for 65% of the ore reserves at that time) as a mechanical or gel precipitate accumulated in a chemically favourable basin near a shore-line just to the south, but described the Lower Zone as a replacement deposit.

A low grade copper-silver deposit was also discovered at about this time, near Tipperary, by Gortdrum Mines Limited. This was a result of geochemical and geophysical examinations of an area selected by Mr GHR Burrill on the basis of a similar geological setting to the Tynagh deposit (see Thompson 1967).

At the commencement of my own study in October 1965, Derry, Clark and Gillatt published a paper on the Tynagh base-metal and iron deposits in which they put forward the suggestion that the primary lead-zinc ore originated contemporaneously with a mud bank complex in an area of active or recent organic growth. The mineralizing solutions were thought to have risen along the zone occupied by the present

North Tynagh Fault and after precipitating the sulphides near the surface, escaped into the sea, where iron and silica remaining in solution were deposited in a protected basin off the edge of the reef.

Factors Controlling Attitudes to Research

Although many European geologists have attributed the genesis of stratabound base-metal deposits to sedimentary processes, this theory was not generally accepted elsewhere before 1953. Between 1953 and 1955 however, papers were published advocating a sedimentary origin for the North Rhodesian Copper Ores (Garlick 1953); the White Pine Copper Deposit, Michigan (White and Wright 1954), and for two deposits in New South Wales, Australia; Broken Hill (King and Thomson 1953) and Bathhurst (Stanton 1955). The affect of these papers on mineral exploration groups was profound, many leaving the pre-Cambrian Shield areas to look for syngenetic copper-lead-zinc deposits in geosynclinal belts, and even in platform areas where shore lines and vulcanicity were in evidence. One company went so far as to call itself 'Syngenore'.

In 1964 I had the good fortune to meet RL Stanton in the Solomon Islands where he was looking for a recent sedimentary base-metal deposit, in a modern example of a 'type' area. I was involved in lagoon bottom sampling in a volcanically active region, and also helped to investigate what proved to be a residual sedimentary iron deposit.

My 'conversion' to the syngenetic theory was complete after visiting the Sullivan lead-zinc mine, and some of the Kootenay Arc mines in British Columbia, Canada. Working as an exploration geologist at the Keno Hill lead-zinc-silver vein deposits, did not threaten my faith. Boyle (1965) had presented a persuasive case for diffusion of ore and gangue elements from the surrounding metamorphosed sedimentary and igneous rocks into the veins. This provided a sophisticated lateral secretion theory for me 'to fall back on' to explain cross cutting features. I determined to research into an extensive stratabound deposit and reinterpret a so-called epigenetic replacement deposit. The method was to attempt an integration of the sulphides as a sediment into the total geological environment. This would mean a search for volcanics and a shore line. I applied to Professor Dunham at Durham University requesting a research project on Kilembe copper mine, Uganda. This being already the subject of a research project at Durham, Professor Dunham suggested instead the newly discovered mineralization in Ireland.

Research Approach

If a syngenetic-diagenetic model for Irish ore deposits were to be acceptable, an extensive metal enrichment had to be demonstrated coincident with the bedding, even at a distance from the ore deposits. Hirst and Dunham (1963) had found high concentrations of lead and zinc in the Marl Slate, the lateral equivalent of the Küpferschiefer, which further supported the syngenetic theory for mineralization in this Zechstein shale. Previously Lurye (1957) had studied the regularities in the distribution of metals in Upper Devonian and Lower Carboniferous carbonate rocks in central Kazakhstan and discovered an enrichment of lead, zinc, silver, barium, manganese and iron in part of the stratigraphic section. He concluded that the development of such trace element concentrations in a certain limestone horizon over a large area represented a primary sedimentary accumulation, and suggested that this may be important in solving the problem of the genesis of the Mirgalimsai ore deposit (situated 15 km south of the sampling area) containing concentrations of these same metals. Influenced by these two papers, I decided to concentrate the thesis on trace element analysis of the Lower Carboniferous Limestone remote from the deposits, and also to examine the lateral extensions of the stratabound ores where possible.

The syngenetic theory also demanded a study of the total geological environment. In Ireland this essentially meant bibliographic research as well as consideration of the metallogenic province. As an undergraduate student I had been very interested in continental drift and I immediately sought to study the entire province as given by the Bullard, Everet and Smith (1965) refit of the continents. This action provided me with extra examples of ore deposits from which generalizations might be drawn. One early predisposition gleaned from visiting the lead-zinc deposits of south British Columbia was that ore deposits could perhaps act as the source of younger syngenetic deposits. There were plenty of Appalachian/ Caledonian deposits that could have provided the metals for the younger sedimentary ore deposits in the Carboniferous. These considerations suggested that the continental refit would also be an important parameter in terms of provenance of the ore deposits.

Thesis Plan

The thesis is in two parts. The first concerns the reconnaissance investigation of the trace element dispersion patterns from certain Irish sulphide deposits. The results of this research indicate whether the deposits are syngenetic-diagenetic as expected, or epigenetic.

The second part consists of a formulation of a hypothesis which attempts to explain the genesis and the siting of the ore deposits.

ACKNOWLEDGEMENTS

Perhaps more important than publications, it is the experts one meets who influence a research approach most. Dr RL Stanton kindled my interest in ore deposits and he and Dr David Mackenzie emphasised the significance of the total geological environment in ore deposition. Professor KC Dunham supervised the project for the first year and I thank him for introducing me to this most interesting ore field. Dr JS Jackson suggested areas for background sampling and also drew my attention to his important work on the Kingscourt Fault.

I thank Irish Base Metals Limited, Tara Exploration Limited and Gortdrum Mines Limited for permission to collect samples from their properties. Members of these companies were most helpful and I had many rewarding discussions with them, especially Dr RW Schultz, Mr B Byrne, Mr N Gillatt, Mr MV O'Brien, Mr A Meldrum, Mr D Whitehead and Mr JL Evans. Also while in Ireland I had stimulating discussions with Professor T Murphy and Dr P Gardiner.

I learnt about the geophysics and structure of the North Atlantic from Dr AP Stacey. I should like to thank Dr A Burgess for his assistance and suggestions regarding stress and strain in the Earth's crust. Mrs Maureen Kaye and Dr JG Holland instructed me in the use of X-ray fluorescence spectrography. Latterly I was fortunate to have the advice of Dr AC McLean while working on Scottish comparisons. Dr M Solomon and Mr I Taylor told me about logic and methodology.

Finally I should like to thank Dr DM Hirst for his constant interest, encouragement, supervision and for critically reading the thesis draft. His suggestions were most helpful and his advice invaluable.

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II GEOLOGICAL ENVIRONMENT

Introduction

The newly discovered base metal ore deposits in Ireland occur in the Lower Carboniferous rocks of the Central Plain, an area of about 40,000 km^2. Ireland itself is situated close to the continental margin.

Precambrian

The oldest rocks, outcropping in the Ox Mountains and in Donegal in the northwest, are schists, gneisses and flaggy siliceous granulites similar to the Moinian of Scotland (Anderson 1948; 1954). Overlying these rocks are metamorphosed Dalradian geosynclinal sediments which also outcrop in the north and west. Lithologically these sediments include black pelitic schists with lesser amounts of quartzite, limestone and metadolerite sills and lavas.

In the extreme southeast of Ireland gneisses, schists, migmatites and folded intrusions of the Rosslare Complex are part of a Precambrian foreland (Crimes and Dhonau 1967). Just to the northwest the Cullenstown Group of schistose quartzites, greywackes and chlorite schists of probable Precambrian age outcrop and presumably bear a similar relationship to the Rosslare Complex as the Moine does to the Lewisian in Scotland.

Lower Palaeozoic

Lower Palaeozoic geosynclinal rocks outcrop in the east and west of Ireland and in inliers of the Central Plain. They include shales, mudstones, silts and greywackes, together with andesitic and acid extrusives and minor intrusives. These rocks are folded, but have suffered only minor metamorphism. Some of the argillaceous rocks have developed slaty cleavage parallel to axes of folding. A large stratabound 'pyritic' orebody occurs in those rocks at Avoca in eastern Ireland and contains chalcopyrite, galena and sphalerite. The trend of the fold axes is subparallel to that of the older groups of rocks; this direction is generally northeast-southwest except in Connaught where it is approximately east-west. Geosynclinal rocks with a possible vertical thickness of 3000 m (Murphy 1952) presumably extend under the Central Plain. Caledonian granite intrusions outcrop in the east, north and west of Ireland. The Galway granite in the west contains molybdenite along part of its margin. The main phase of folding and metamorphism of Dalradian geosynclinal rocks took place before ealy Arenig times (Skevington 1971).

Old Red Sandstone

The Lower Palaeozoic rocks were climactically deformed during the late Silurian or early Devonian period. The first molasse sediments, derived from the Caledonian Mountains, seen outcropping in Ireland are the Downtonian Sandstones of the Dingle Peninsula and the Croughaun Beds of the Comeragh Mountains 160 km to the east (Shackleton 1940; Capewell 1957). These sediments suffered intense folding in Lower (George 1962) or Middle Devonian times (Allen 1962).

Molasse sediments belonging to the Lower division of the Old Red Sandstone occur in the Midland Valley of Ireland. The floor of this faulted valley sank intermittently and andesitic lavas were extruded from 'associated' volcanoes. The Middle Devonian orogenic movements followed, after which the Midland Valley Trough re-subsided and Upper Old Red Sandstone conglomerates, red and purple sandstones, flags, shales and grits were deposited in this foredeep (Charlesworth 1963).

To the south, in central Ireland, rivers flowing southwards deposited coarse sandstones in their channels, and silts over larger areas during times of flooding (Hudson and Sevastopulo 1966). The thickness of these beds is not known, but is less than 400 m on the anticlinal inliers (between 180 and 360 m at Tynagh, Schultz, 1962). These rivers drained into a cuvette in southwest and south central Ireland, known as the Munster Basin (Capewell, 1965). The trend of this basin was essentially eastwest, except in the east where a Caledonian bias operated. The maximum subsidence was in the north of the basin where 6000 m of alluvial clastics were deposited.

These sediments were derived from the north, northeast and east and become finer grained upwards and to the south. They probably belong entirely to the Upper Old Red Sandstone Group. Capewell (1965) has discovered south facing buried cliffs beneath the sandstones and conglomerates in the Slieve Mish area and suggests from this, and from the location of the isopachytes, that the basin had a faulted margin in the north.

Towards the close of the Devonian, sandstones and conglomerates were deposited in a shallow lake in the south of Ireland. These sediments, white and green in colour due probably to reduction by planty matter, are known as the Kiltorcan Beds and are remarkable for their anomalous contents of copper and barytes (Jukes 1861).

Carboniferous

In the extreme south some marine intercalations across a delta took place in the Famennian (Upper Devonian). This southern sea swept rapidly across the low lying plains of south and central Ireland in lower Tournaisian times, so that beds belonging to the K zone are found to conformably overlie Upper Old Red Sandstone sediments as far north as Tynagh where Jackson has recorded about 45 metres of K zone (Schultz 1966a). To the southwest, in County Clare and north County Limerick, K zone sediments (including the Modiola phase) are between 5 and 20 m thick (Douglas 1909); Shephard-Thorn 1963; Hudson and Sevastopulo 1966). Even in northern Ireland, in Counties Tyrone and Fermanagh, Sheridan, Hubbard and Olroyd (1967) have

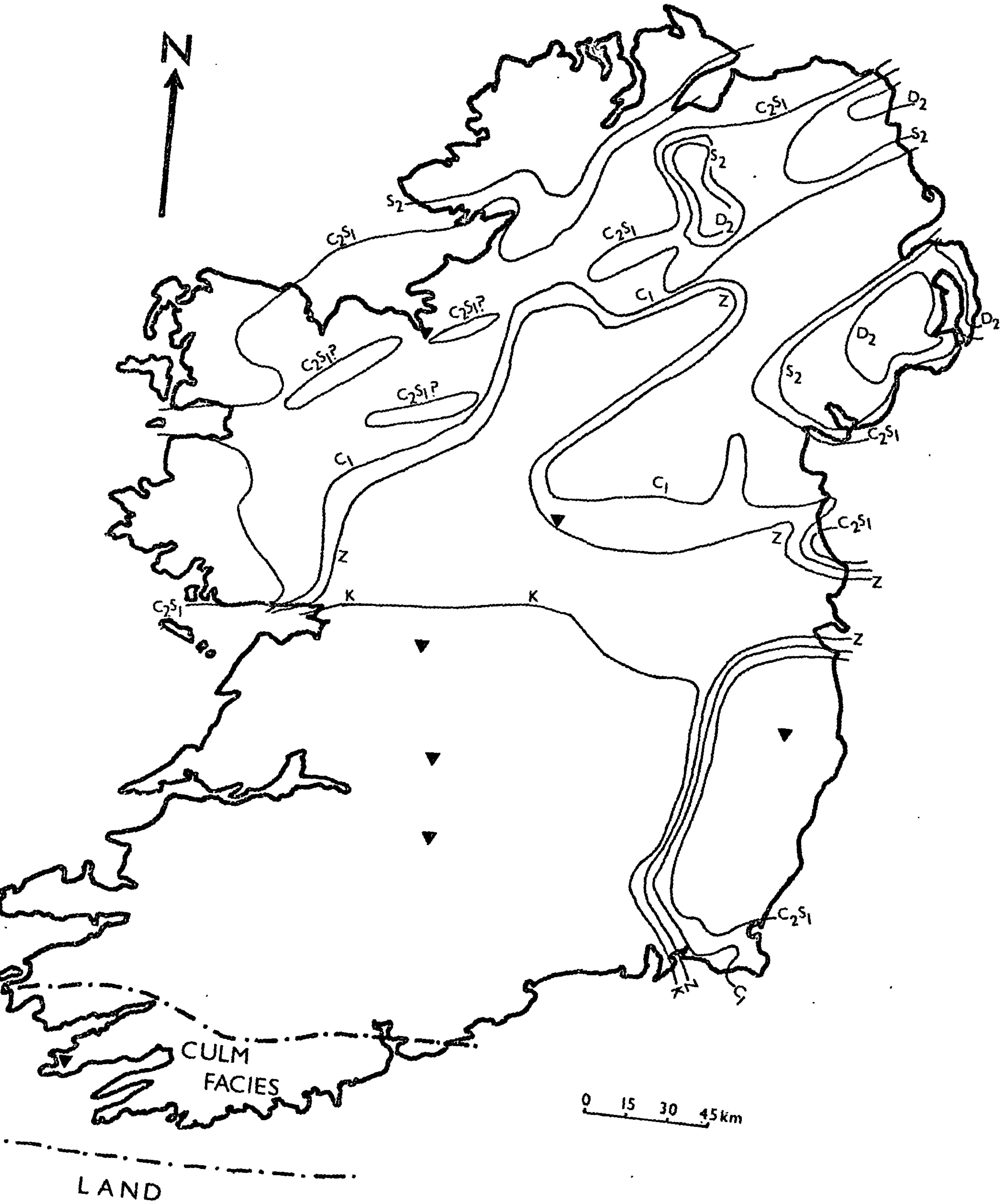

N
C_2S_1
D_2
S_2
S_2
D_2
S_2
C_2S_1
C_2S_1
C_1
Z
C_2S_1?
C_2S_1?
C_2S_1?
D_2
D_2
S_2
C_2S_1
C_1
C_1
C_2S_1
Z
Z
Z
C_2S_1
K
K
Z
C_2S_1
KN
C_1
CULM
FACIES
0 15 30 45 km
LAND

Figure 2 - 1

Map showing the stages in the transgression of the Dinantian sea. (Based on Charlesworth 1963 with modifications from Sheridan, Hubbard and Olroyd 1967 and Naylor 1969). The ore deposits named in Figure 1 - 1 are shown as red triangles.

reported a microfauna typical of middle to upper Tournaisian zones overlying the continental Upper Old Red Sandstone with apparent conformity. Figure 2 - 1 shows the stages in the transgression of the Dinantian sea.

The Dinantian strata in the extreme south of Ireland (south of a line from Sneem to Cork Harbour) are quite different to those on the shelf to the north. They consist of a marine succession of sandstones, grits and mudstones of the Culm facies 2,500 metres thick. It is necessary to postulate a land mass with high relief to the south of this downwarp in the Lower Carboniferous in order to explain the thickness and lithology of this Carboniferous Slate.

Of the Tournaisian limestone shales and bedded limestones deposited on the stable shelf of central and south-central Ireland, Hudson Clarke and Brennand (1966) have remarked that differences in thickness of the various formations in different areas are probably more apparent than real. In central, west and south Ireland these rocks are overlain by a carbonate mudbank complex of upper Tournaisian and lower Viséan age, called hereafter the Waulsortian. Lees (1961) suggests that the banks were formed in situ and that organisms, probably plants and to a lesser extent bryozoa, gave some support to these structures. Their base is diachronous and the thickness variable (Figure 2 - 2). The thickest accumulations took place in the Shannon region, in the west, and the Cork area to the south. Lees says: "It is almost certain that the existence of an unstable "basin" or "trough" in the Shannon area played a large part in the original localization" (of the bank complex). He tentatively suggests that this argument holds good for the Cork area also.

Hudson, Clarke and Brennand (1966) consider that there may have been mid-Dinantian earth movements which caused uplift of the Waulsortian Limestones. As evidence they point to the limestone breccias above the Waulsortian mudbank at Castle island, County Kerry, and in parts


N
SLIGO
LIMERICK
CORK
0
50km
metres
2000
1000
0
SLIGO
LIMERICK
CORK
Volcanics
Mud-belt facies
Tournaisian limestones
Upper Viséan Limestone
Lagoon facies
Offshore clastics
Tournaisian-Viséan boundary
Waulsortian bank complex
Land

Figure 2 - 2

Top diagram is a palaeogeographic map showing the distribution of the major lithofacies at the close of Waulsortian times (modified from Lees 1961). Major ore deposits shown as red triangles.

Bottom diagram is a section showing lateral changes in thickness and facies in Dinantian rocks. (Based on George 1958 with modifications from Lees 1961).

of County Limerick. Similar breccias occur at Tynagh (Schultz 1966a). Lamont (1938) suggested that the Nassauian (mid-Dinantian) disturbance caused fast erosion of the land mass east of Dublin and that a supply of mica helped to form C_2S_1 rocks in that region. Charlesworth asserts that the Nassauian disturbance (early C_2S_1) was responsible for the Rush and Lane Conglomerates, in the east, and the recurrence of the arenaceous facies in the northwest. He also tentatively correlates the volcanic eruptions in County Limerick, at Ballycastle, County Antrim and at Philipstown, County Offaly, with this phase.

Bedded limestones followed the deposition of the Waulsortian bank complex in most of Ireland.

A widespread non-sequence separated the upper Viséan from the overlying Upper Carboniferous. Only a few outliers of what must have been a nearly continuous Upper Carboniferous cover still exist. Sandstones, shales and minor conglomerates were derived mainly from the north, although some of the sediments in the extreme south were derived from a southerly source (Charlesworth 1963).

Much of this sedimentation took place in subsiding basins. Notable amongst these was the Foynes Trough, trending east-west (Hodson and Lewarne 1961). This is on the site of the mid-Dinantian trough in which the thick Waulsortian mudbank accumulated. In general the overstep and overlap of the beds permitted Hodson (1959) to deduce the whereabouts of three east-west troughs in Ireland at that time. These were situated in the south, centre and northwest of Ireland.

The Coal Measures of Ammanian age were the last Carboniferous rocks to be deposited.

The Armorican Orogeny

There is some disagreement regarding the effect of the Armorican Orogeny in Ireland. Conventionally the mid-Dinantian and Viséan/

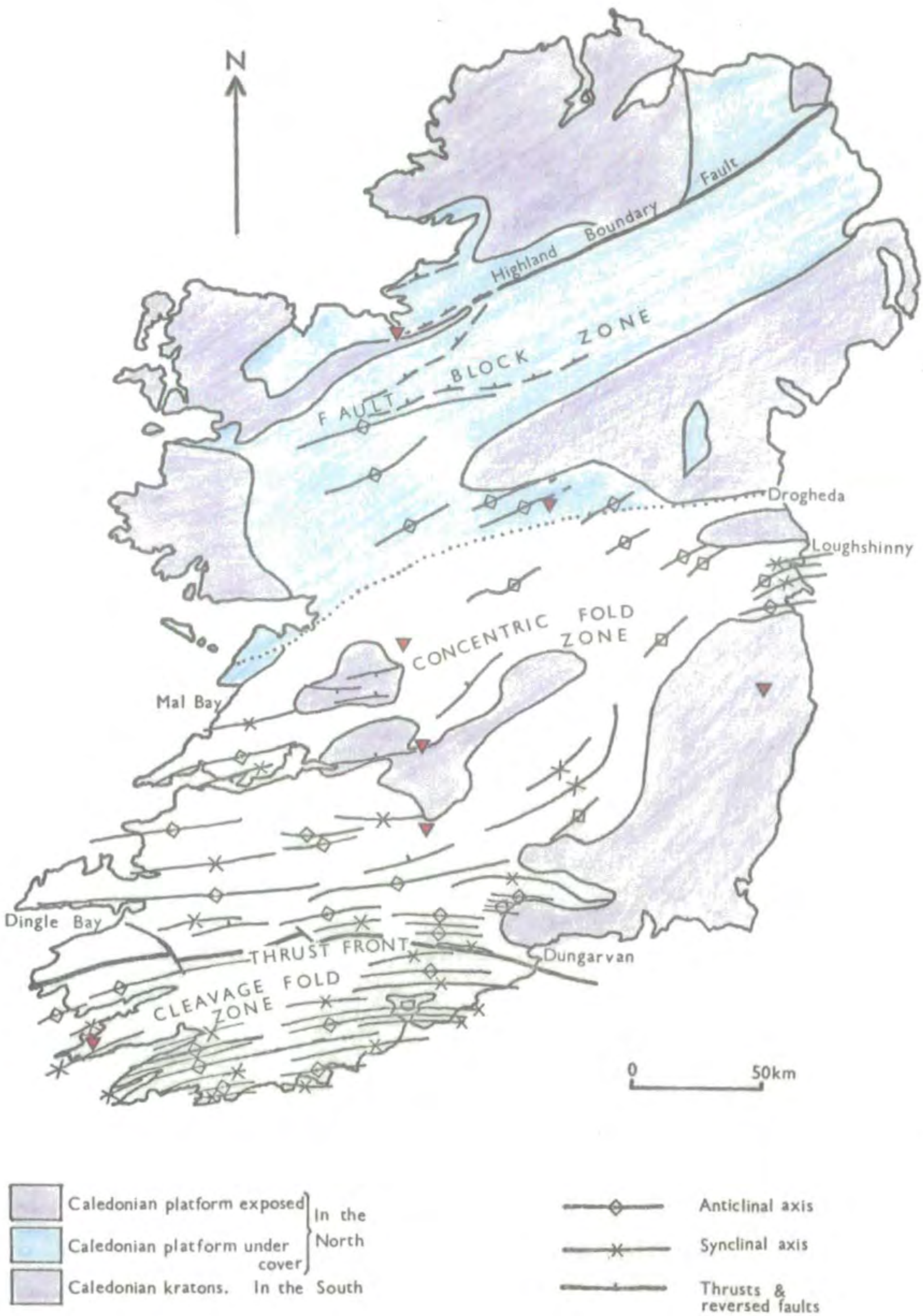

N
Highland Boundary Fault
FAULT BLOCK ZONE
Drogheda
Loughshinny
CONCENTRIC FOLD ZONE
Mal Bay
Dingle Bay
THRUST FRONT
Dungarvan
CLEAVAGE FOLD ZONE
0 50km
Caledonian platform exposed
Caledonian platform under cover
In the North
Caledonian kratons. In the South
Anticlinal axis
Synclinal axis
Thrusts & reversed faults

Figure 2 - 3

Analysis of Armorican structures in Ireland simplified from Gill (1962). Major ore deposits shown as red triangles.

Namurian discontinuities are respectively ascribed to Nassauian and Sudetic Phases of the Hercynian. Simpson (1962) suggests that the Nassauian Phase be regarded either as a very minor parorogeny affecting shelf seas immediately north of the geosyncline, or alternatively as merely an erosional phase in a cyclical epeirogenic warping which continued throughout the Lower Carboniferous independent of movements in the Variscan geosyncline. Simpson also casts doubt on the Sudetic Phase as there is no evidence for such an orogenic episode in the geosyncline itself.

What is more certain is that there were two distinct phases of strong folding in post Westphalian times in Ireland south of a line from Dingle Bay to Dungarvan (the Armorican Front). This is Gill's Zone of cleavage and folding (Gill 1962 and see Figure 2 - 3).

Many of the folds are broken by east-west dextral shears developed penecontemporaneously with the folding. Northeast-southwest trending faults are also common, and numerous northsouth faults frequently terminate against the dextral shears (Dawson-Grove 1955).

There was very little igneous activity in this zone. North of Bandon in County Cork there is an outcrop of olivine-dolerite in Carboniferous slate, but this rock type is similar to volcanics better developed further north and seemingly unrelated to the Armorican Orogeny. More unusual are the intrusive tuffs (Coe 1959; 1966) at Black Ball Head in the southwest. Coe shows that an early phase of folding was followed by the intrusion of pipes and intersecting dykes which themselves have been subsequently deformed. The intrusive tuffs in the pipes were emplaced probably by the action of hot, dry gasses. They contain fragments of local rocks but also marble,hornblendite and gneiss. Coe suggests that the tuffs may have arisen from a concealed pluton, and supports this by pointing out that the regional metamorphism is not simply dynamic in nature and that sulphide mineralization at Allihies, close by, may have been derived from magmas at depth (see Chapter Vll). Charlesworth (1963) also suggests that other plutons may be indicated by the large negative anomalies in this southern region. Naylor and Jones (1967), however, believe that one of these anomalies is more easily explained in terms of the huge thickness of Old Red Sandstone in the area.

The line dividing the zone of cleavage and folding from the zone of concentric folding to the north takes the form of a thrust between Killarney and Mallow, with a dip of 40° to 50° to the south. The concentric folds were also built in Westphalian times, and this zone may itself be divided into a belt of steeper folds with local thrusting, south of a line from Mal Bay to Loughshinney.

To the north, but south of a line from Galway to Drogheda, the folding is more open. The dominant trend of the folds in this second structural zone is Caledonoid due to basement control except where the Carboniferous rocks are especially thick and competent (Weir 1962).

A zone of fault blocks developed on the Caledonian platform, lies to the north of the line from Galway to Drogheda. Here deformation is slight with fault block movements and subsidiary warping being the main effects, although there are some gentle folds in the south of this zone which indicate compression (Oswald 1955).

Most of the faults in the two northerly structural zones are of normal type and trend eastwest or northeast-southwest. There is some evidence that sinistral slip has taken place along some of these faults (Anderson 1954). In the newly discovered mining areas all the faulting appears to be normal in character. Shelford (1963) has reinterpreted the Slievenmuch Fault as a thrust, especially emphasising the southerly dip of the downthrown Carboniferous rocks to the north. Thompson (1967) comments on a similar condition in the Gortdrum mine area (10 km to the north), but, citing Hamblin, points out that such 'reverse drag' along normal faults is not unusual. So Shelford's (1963) contension that this fault indicates a 30 km extension north, of the position of the Armorican front, is 'not proven'. It is possible to argue that the fault was normal at first and then reversed during the Armorican.

Permian, Mesozoic and Tertiary (Charlesworth 1963)

Permian sediments are now restricted to the northeast of Ireland. Red sandstones and conglomerates rest with strong unconformity on older rocks. A brief incursion of the Zechstein Sea from the east caused deposition of the Magnesian Limestone. Red marls and gypsum beds were also deposited.

Mesozoic rocks may have originally covered large parts of Ireland but again they are confined to the northeast. In this region too, there are extensive tracts covered with plateau and flood basalt levels of Tertiary age. Basic dykes and central intrusive complexes of the same age are also common.

III THE GEOCHEMICAL ENVIRONMENT OF MINERALIZATION, BACKGROUND STUDIES

General Features of the Sulphide Deposits

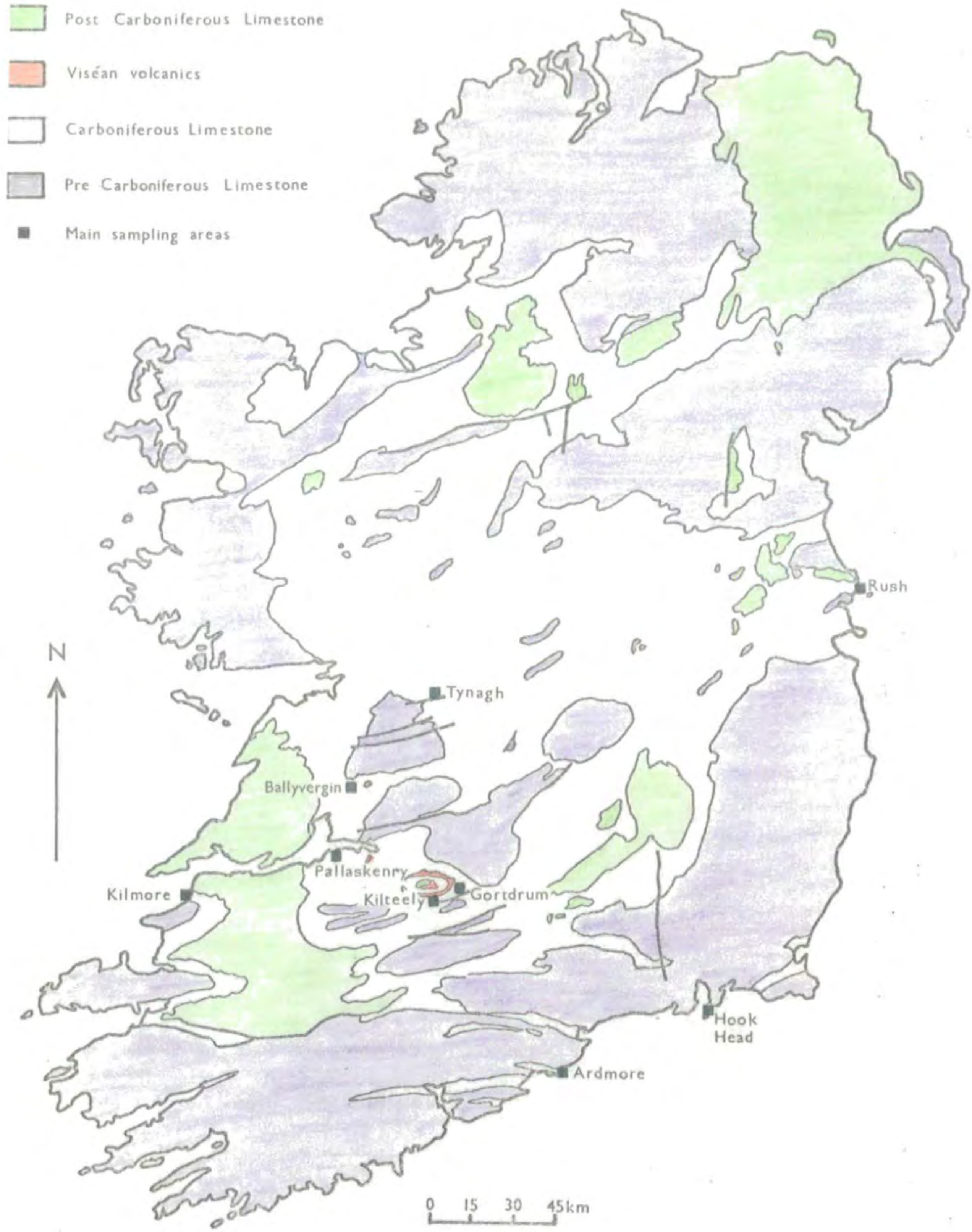
The deposits occupy Dinantian limestones, limestone shales and sandstones (Plate 1) and occur near the mapped junction between these rocks and the Old Red Sandstone (or Moine in the case of the Abbeytown deposit). Commonly it is a faulted junction, but there are exceptions.

Aim

The purpose of this part of the research programme is to study the distribution of lead, zinc, copper with associated elements in the Upper Devonian and Lower Carboniferous sedimentary rocks that act as hosts to the ore deposits. The results should provide the background concentrations of trace elements against which trace element aureoles may be contrasted. Enrichments may be expected in certain beds if submarine exhalations of mineralizing fluids took place in the Dinantian Sea.

Sampling and Sampling Error

The ore deposits occur in a variety of lithologies and stratigraphic horizons necessitating collection from all the lithological rock types comprising each stratigraphic unit. It is normally assumed that the trace element concentrations represent syngenetic deposition albeit with some minor 'within sample' diagenetic movements. This assumption may not be justified for we know from recent sampling of marine sediments that there is much migration of ions in the top metre or so (Brooks and coworkers 1968). Also during diagenesis trace metals could be leached out of the rocks by circulating brines. Moreover in oxidising conditions base-metals may not be precipitated at all on the sea floor, or if so, merely as easily soluble carbonates. In conditions where argillaceous sediments were deposited we may expect any trace



Post Carboniferous Limestone
Viséan volcanics
Carboniferous Limestone
Pre Carboniferous Limestone
Main sampling areas
N
Rush
Tynagh
Ballyvergin
Pallaskenry
Kilmore
Kilteely
Gortdrum
Hook Head
Ardmore
0 15 30 45km

Figure 3 - 1

Simplified geological map of Ireland copied from the Geological Survey of Ireland 1:750,000 geological map, 3rd edn 1962, showing sampling areas cited in chapters III to VI.

metals escaping from springs to have been adsorbed by clays, and a proportion to have been eventually incorporated into a sulphide phase. Unfortunately, shales are susceptible to weathering, and surface oxidation may destroy the original trace element suite.

Apart from these shortcomings, there may be a serious built in error in that the samples taken are not representative of the rock body as a whole because of the nature of the collection sites. Sections that had been palaeostratigraphically mapped and described were chosen as collecting areas (Figure 3 - 1). The palaeostratigrapher obviously picks continuous sections through the succession as his type area. The very existence of a continuous exposure depends upon an inclination of the strata. In Ireland these sections are coastal. Usually the beds dip at about 25° although readings of up to 60° are recorded. These sections are similar in their structural setting to those of the base-metal deposits, and dissimilar from the essentially flat lying Upper Devonian and Lower Carboniferous rocks away from the Old Red Sandstone inliers. It is possible that the inclined rocks sampled in the coastal sections overlie a fault at depth, and therefore some elements could have been introduced epigenetically.

Epigenetic enrichment may also have come about by precipitation of trace elements contained in fluids expelled from subsiding basins down dip from the sampled sections.

A 3 kg hammer was used to obtain 2 kg samples from any required bed at exposures. No collection was made at or near veining. Because of rock variation and consequent differential weathering there was a possible bias for limestone and sandstone and against shales and limy shales. This bias may have been reduced by sampling the less resistant rocks where possible and subsequently dividing non-arenaceous sedimentary rocks into different groups according to their rubidium content on the assumption that this element provided a rough measure of the clay content (Table 3-1, below). The correlation coefficient of rubidium with alumina (179 comparisons) is 0.93.

TABLE 3 - 1

SEDIMENTARY ROCK CLASSIFICATION USED IN THIS THESIS	CLASSIFICATION METHOD
OLD RED SANDSTONE:	
Sandstones	visual
Shales	visual
CARBONIFEROUS:	
Dolomites	Mg content semi quantitative XRF
Waulsortian Limestones	visual
Other limestones	< 40 ppm Rb
Shaly limestones	40 - 100 ppm Rb
Limestone shales and shales	> 100 ppm Rb
Sandstones	visual
Siltstones	visual

Apart from an outer skin, the limestones appeared to be unweathered but the sandstones, porous dolomites and shales (see Plate 2) have suffered some chemical weathering.

For the foregoing reasons the sampled population does not correspond to a perfect or target population, and we must be careful in drawing inferences between the outcrop samples and drill core samples from mine areas.

Sample Preparation

The samples were initially split in a hydraulic cutter, and where possible weathered surfaces removed. They were then passed through a Sturtevant 50 x 150 mm roll-jaw crusher and a quartered aliquot fed into a Tema tungsten carbide laboratory disc mill. The resulting powder of less than 40 microns particle size, was used in all subsequent analyses.

Analytical Techniques and Error

Most of the analyses were carried out using a Philips X-ray fluorescence spectrometer (PW 1540) in the Geology Department at Durham University. The trace elements analysed were chosen either on the basis of their existence in the ore deposits, or because they helped to describe the rock and indicate subsequent changes in its composition. For this reason, 12 mixed ores collected from Tynagh, Abbeytown and the County Clare deposits, by Professor Dunham were scanned on the spectrograph. They contained large amounts of lead, zinc, copper, iron and arsenic; barium, manganese and cadmium were common and cobalt, nickel, molybdenum, antimony and silver occurred occasionally, or in trace amounts. Examples of limestone collected by Professor Dunham failed to show any silver, cadmium or antimony but did contain strontium and rubidium.

From these results I decided to analyse for lead, zinc, copper, nickel, iron, arsenic, barium, manganese, sulphur, rubidium and strontium, because of their presence in the ores or limestones. Cobalt was not analysed because the tungsten carbide disc mill was bonded with this element. Silver, cadmium and antimony were also left out because they were below their detection limit in the limestones. Molybdenum was analysed in some rocks by a colorimetric method (Stanton 1966) and mercury in some samples using the sensitive Mercury Vapour Meter at Imperial College. This last element was analysed because of its common occurrence in dispersion aureoles in many ore fields (Saukov 1946; James 1964). Some of the rocks were also analysed for major elements using the X-ray fluorescence spectrometer.

Three major causes of error in X-ray spectrometry have been noted by Liebhafsky and Winslow (1958). The first is instrument instability arising from variations in the lattice spacing of the analysing crystal and instability of the electronic circuitry under the influence of ambient temperature variation. In Durham this is minimised by housing the equipment in a small room with an air conditioner to ensure constant temperature. A second cause is that due to an increase in radiation intensity with decreasing particle size. This is overcome by using powders of constant fineness. The frequency distribution of the surviving analytical error was determined by reloading and counting the same specimen twice each day.

The fact that absorption and emission of X-rays is a function of the entire chemistry of the sample constitutes the third cause of error. The total chemical composition controls the extent to which any element in the material affects the fluorescent radiation (Liebhafsky and coworkers 1960), so different sets of standards are made for each rock type. Accuracy was measured by comparison with the US Geological Survey Reference Silicates G1 and W1 and National Bureau of Standards, Argillaceous Limestone No 1A, and Dolomite No 88 (Appendix 1).

Standards

Standards were prepared by spiking a limestone, sandstone, shale, ironstone and an acid and basic igneous rock. A master standard was made up to contain 2500 ppm of each of the group of trace elements, plus the original concentration in the rock, and mixed in a spex mixer for five one minute intervals in different orientations, and then for three separate hours again changing the orientation of the vial. By adding aliquots of the standard base to the master, and mixing, a series of standards containing an addition of 50, 100, 200, 300, 500, 750 and 1000 ppm was produced.

Contamination

Sample contamination can take place at two distinct stages. Firstly during collection, handling and preparation, a sample is in contact with steel equipment. The equipment used was kept clean and no ores were handled at the same time.

The second stage is that of analysis, X-ray tubes being commonly contaminated. This was neutralized by measuring the intensity of the peak for each element using a pellet of 'spec pure' silica and recording it as a fraction of the tungsten line L_{ι} intensity. Lead, copper and nickel were present and therefore the intensity of the tungsten L_{ι} peak was measured for every sample and a correction applied for the contamination, using this ratio.

Operating Conditions

The operating conditions are shown in Appendix 1. There was interelement interference in the case of lead and arsenic; the arsenic K_{α} line overlaps the lead L_{α} line so that arsenic K_{β} and lead L_{β} lines were used. The detection limits of these two elements are accordingly high.

Accuracy, Precision and Detection Limits

The detection limit was taken as the concentration that resulted in a line intensity equal to three times the standard deviation of the background counts (Campbell and coworkers 1959). The detection limits, as well as precision and accuracy, are shown in Appendix 1.

Determination of Mercury

A number of samples were analysed in duplicate for mercury, at Imperial College, using a Sensitive Mercury Vapour Meter. This instrument which makes use of the absorption by mercury of ultra violet light, was developed by James and Webb (1963). The accuracy, precision and detection limits are shown in Appendix 1.

Rapid X-ray Fluorescent Partial Major Element Analysis

About 300 Lower Carboniferous rock powders were analysed for calcium aluminium,silicon, iron and sulphur. The rock was mixed with a few drops of Mowiol, backed with borax, and pelletized using a hydraulic press at 5,000 lb/sq in. A Philips X-ray fluorescence spectrometer

PW 1212 was used, the technique adopted being closely similar to that described by Holland and Brindle (1966). The standards used were the National Bureau of Standards sample numbers 1A and 88 (Argillaceous Limestone and Dolomite respectively) and US Geological Survey Reference Silicate Rocks. In the construction of the matrix block, calcium was recorded as carbonate, sulphur as the element, and the remaining elements as oxides.

Rush Section (Area 5)

Thirty two samples of Dinantian rocks were collected from stratigraphic horizons described by Smyth (1915) with modifications by Smyth (1951) and Hudson, Clarke and Sevastopulo (1966). Table 3 - 2 shows the zones, lithologies and average trace element concentrations of these rocks (refer also to Plate 1). Individual analyses are given in Appendix 2.

The sediments were formed near a shore line and Mately and Vaughan (1906; 1908) have suggested that the relative thicknesses of the deposits indicate the presence of a river mouth nearby. Faults of small throw are common along the section but appear to be especially abundant in the upper part of the Rush Conglomerates and in the Supra Conglomerate Limestones. The steepest dips (up to 65^{o}) are also achieved in the conglomerates. In the light of these facts the high concentrations of zinc, barium, lead, arsenic and copper in the conglomerates may not be simply ascribed to original sedimentry concentration. Other possibilities are that the enrichments result from later mineralizing waters from depth taking advantage of faults, or of the permeable conglomeratebeds.

The Rush Conglomerates contain Lower Palaezozoic fragments derived from a land mass to the south and east. Charlesworth (1963) has suggested that the conglomerates are a result of concurrent faulting and basin formation related to the Nassauian disturbance. If the trace element patterns are syngenetic, the metals could have been derived

TABLE 3-2 Rush section (Area 5) summary of results, (n = number of samples, R = range of values, M = Mean)

Zone	Succession	Classification		Pb ppm	Zn ppm	Cu ppm	Ni ppm	Ba ppm	Sr ppm	Rb ppm	As ppm	Mn ppm	Hg ppb	S %	SiO_2 %	Al_2O_3 %	$CaCO_3$ %	Fe_2O_3 %
D_2	Posydonomya	Limestone	n	4	4	4	4	3	3	3	1	1	2	1	1	1	1	1
	Limestone		R	<17-17	14-29	18-33	23-37	260-306	973-3328	<5-17	<25	98	35-93	0.57	24.4	1.9	70.1	1.6
			M	<17	18	25	30	281	1973	~10			64					
D_1	Dolomite	Dolomite	n	4	4	4	4	3	2	2	1	1	1	1	1	1	1	1
			R	<17	<6	9-51	<8-28	160-204	38-46	<5-9	<25	5950	23	0.07	2.9	0.0	52.3	6.0
			M	<17	<6	25	~17	189	42	~6								
C_2S_1	Limestones	Limestone	n	9	9	9	9	5	7	7	2	3	1	3	3	3	3	3
			R	<17-30	<6-43	<8-16	<8-28	206-266	277-463	<5-33	<25	2032-5250	28	0.20-0.38	5.1-14.1	0.2-2.4	69.5-89.6	1.0-3.9
			M	~16	~19	~9	~16	233	349	~13		3145		0.28				2.2
C_2S_1	"	Shaly	n	5	5	5	5	3	3	3	—	—	3	—	—	—	—	—
		limestone	R	<17-34	36-237	23-45	33-72	320-346	266-290	57-69			60-150					
			M	~23	108	30	51	327	276	64			98					
C_2S_1	Rush	Limy	n	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1
	Conglomerates	shale	R	47-50	198-282	48÷50	86-110	1670-1804	245-254	115-190	52	602	106	0.15	48.7	14.4	16.2	7.3
			M	49	240	49	98	1737	250	153								
C_2S_1	"	Shaly	n	2	2	2	2	2	2	2	1	1	—	1	1	1	1	1
	"	limestone	R	28-32	122-440	23-27	30-56	1650-3176	404-449	37-45	35	1418		0.22	31.6	7.0	48.1	5.6
			M	30	281	25	43	2413	427	41								
C_2S_1	Rush	Limestone	n	1	1	1	1	1	1	1	1	1	—	1	1	1	1	1
	Slates		R	23	60	28	38	280	1091	23	<25	403		0.13	15.9	3.3	74.1	2.4
C_1	"	Limestone	n	2	2	2	2	1	1	1	—	—	1	—	—	—	—	—
			R	<17-39	22-55	18-22	33-40	252	993	20			33					
			M	~24	38	20	37											
Z_2	"	Limestone	n	3	3	3	3	3	3	3	1	1	2	1	1	1	1	1
			R	<17-21	13-18	14-26	28-50	250-350	936-1218	10-36	<25	891	42-57	0.26	19.6	3.8	69.5	2.6
			M	≤17	16	20	40	293	1089	20			50					

either from mineral enrichments on the adjacent land mass or from submarine or subaerial mineral springs. Further sampling and analysis of the beds and their lateral equivalents could clarify the issue.

Manganese is high in the C_2S_1 limestones.

The presence of 51 ppm of copper in one sample of a D_1 dolomite may relate to a vein containing copper ore close by, at Loughshinney (Cole 1922).

Hook Head and Ardmore (Area 14)

Thirty nine samples were collected at Hook Head from the Lower Carboniferous succession as described by Smyth (1930) and modified by George (1960). According to George these rocks are Tournaisian and so twelve samples were taken at Ardmore spanning the Tournaisian-Viséan boundary (Smyth 1939). Fifteen samples were collected from the top 120 m of the Old Red Sandstone at Hook Head. Full results are presented in Appendix 2 and average trace element concentrations are given in Table 3 - 3.

The Old Red Sandstone is composed of conglomerates and red shales. A conglomerate bed about 3 m thick and 100 m below the boundary was visibly stained with malachite and analysis of two samples of this rock revealed copper contents of 135 and 652 ppm. Copper was also enriched (177 ppm) in a silt 7 m above the conglomerate (Appendix 2). These copper rich beds may be a lateral equivalent of those Upper Old Red Sandstone beds in County Cork also enriched in copper (Jukes 1861), the origin of which is in some dispute. A conglomerate 45 m below the Carboniferous-Old Red Sandstone boundary was found to contain 74 ppm copper.

The Old Red Sandstone is overlain comformably by Tournaisian rocks (see Plate 1). Some samples from beds of K_1 age (dipping 20° south) contain anomalous concentrations of lead and zinc although the uneven distribution of these elements in a single bed and the permeable

TABLE 3-3 Hook Head and Ardmore sections (Area 14), summary of results

Zone	Succession	Classification		Pb ppm	Zn ppm	Cu ppm	Ni ppm	Ba ppm	Sr ppm	Rb ppm	As ppm	Mn ppm	Hg ppb	S %	SiO_2 %	Al_2O_3 %	$CaCO_2$ %	Fe_2O_3 %
C	Waulsortian	Waulsortian	n	9	9	9	9	5	5	5	3	2	4	3	3	3	3	3
	Bank Complex	Limestone	R	<17- 21	<6- 27	<8- 16	<8-29	186-226	180-225	<5- 9	<25- 28	<30	23-46	0.00-0.03	0.7- 0.9	0.3- 0.5	96.0-97.7	0.1-0.2
	(Ardmore)		M	<17	~7	~8	~10	199	201	<5	<25		33	~0.01				0.2
C	Shale	Shaly silt	n	1	1	1	1	1	1	1	–	1	–	1	1	1	1	1
	(Ardmore)		R	24	245	33	200	530	65	208		1509		0.02	66.4	14.0	0.0	3.7
C	Black	Limestone	n	2	2	2	2	1	1	1	–	–	2	–	–	–	–	–
	Limestone		R	<17- 19	25- 37	<8- 17	21-25	180	449	15			41-49					
	(Ardmore)		M	~15	31	~10	23						45					
C_1	Limestone	Limestone	n	12	12	12	12	7	7	7	3	3	4	3	3	3	3	3
	(Hook Head)		R	<17- 30	<6-108	<8- 18	<8-28	196-276	270-806	<5- 16	<25-33	<30-82	20-37	0.15-0.26	16.2-21.3	0.9- 3.7	69.3-78.4	0.5-1.9
			M	~14	~36	~9	~15	236	431	~11		~47	29	0.20				1.3
C_1	Dolomite	Dolomite	n	4	4	4	4	2	3	3	2	2	1	2	2	2	2	2
			R	<17- 31	<6- 79	<8- 15	<8-19	170-216	41- 58	7- 20	<25- 34	150-265	23	0.05-0.08	2.2- 7.5	0.3- 1.5	51.5 52.6	0.4-1.2
			M	~17	~35	~7	~14	193	51	13	~24	208		0.07				0.8
Z_2	Michelina	Limestone	n	4	4	4	4	2	2	2	–	–	1	–	–	–	–	–
	Favosa Beds		R	18- 31	40- 96	<8-14	<8-16	200-210	223-442	<5			29					
			M	24	64	~9	~8	205	333									
Z_1	Michelina	Limestone	n	3	3	3	3	2	2	2	1	1	2	1	1	1	1	1
	Favosa Beds		R	<17	<6- 16	8- 14	<8-17	236-238	355-513	6-10	<25	265	40-48	0.11	4.5	0.8	89.2	1.1
			M	<17	~11	11	~8	237	434	8			44					
Z_1	Michelina	Limestone	n	1	1	1	1	1	1	1	1	1	–	1	1	1	1	1
	Favosa Beds	shale	R	<17	52	16	86	440	164	180	26	217		0.02	52.8	16.8	12.7	6.2
K_2	Fish Shales	Shaly	n	3	3	3	3	1	1	1	1	1	2	1	1	1	1	1
		Limestone	R	<17-20	15- 27	11-15	23-30	364	145	45	<25	2307	29-48	0.25	29.4	4.9	44.6	6.6
			M	~13	19	13	27						39					
K_2	Fish Shales	Limestone	n	3	3	3	3	3	3	3	1	1	–	1	1	1	1	1
		shale	R	<17- 40	53- 56	16-20	65-75	405-515	128-177	154-188	36	683		0.16	53.6	15.4	14.0	6.0
			M	~24	55	18	69	462	158	165								
K_1	Grey Sandstone	Shale	n	2	2	2	2	2	2	2	2	2	–	2	2	2	2	2
	and Transition		R	<17- 26	30- 40	26-45	70-75	340-535	79-121	184-222	84-138	<30-361		0.15-0.50	60.5-65.8	19.8-20.2	0.0-3.8	3.8-3.9
	Group		M	~17	35	36	73	438	100	203	111							3.9
K_1	"	Red sandstone	n	4	4	4	4	4	–	–	–	–	–	–	–	–	–	–
			R	<15-165	<5-123	<7-92	<7-41	195-372										
			M			43	21	259										

Zone	Succession	Classification		Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
K_1	Grey Sandstone	Grey sandstone	n	3	3	3	3	1	1	1	–	–	2	–	–	–	–	–
			R	<15-102	15-1570	10- 22	11-13	438	65	37			57-133					
			M			15	12						95					
	Old Red Sandstone	Shale	n	7	7	7	7	7	–	–	–	–	–	–	–	–	–	–
			R	<15-21	19- 53	8-117	31-73	340-606										
			M	<15	39	30	60	447										
	"	Sandstone and conglomerate	n	8	8	8	8	8	–	–	–	–	–	–	–	–	–	–
			R	<15	<5- 22	<7-652	<7-29	195-446										
			M	<15	11		13	302										

nature of this sequence argue against a syngenetic enrichment. A diagenetic or epigenetic origin accords more directly with the analytical results. Arsenic is also high in the K_1 shales.

The trace element concentrations in the remainder of the succession are not remarkable apart from a sample of shaly silt collected from below the Waulsortian which contains 245 ppm of zinc.

Castleisland and Tralee (Area 13)

The few samples collected from this area (stratigraphy from the one inch to the mile Geological Survey of Ireland map 162) have unremarkable trace element contents (see Appendix 2).

Pallaskenry and Foynes (Area 9)

Fifty two samples of Old Red Sandstone and Lower Carboniferous rocks were collected from between Pallaskenry and Foynes (16 km west of Pallaskenry) on the south shore of the Shannon. The stratigraphic succession has been described by Shephard-Thorn (1963) (see Plate 1). Some points concerning the stratigraphy require amplification. The Mellon House Beds are about 12 m thick and comprise shales, silts, calcareous sandstones and argillaceous limestones. They are assigned to the K_m zone, but are a lagoonal phase and not a strict stratigraphic horizon. The Ringnoylan Shales (completing the Lower Limestone Shales) follow and belong to the K and Z_1 zones. The Z_2 zone is represented by the Ballysteen Limestones, the top beds of which are "back reef facies" to the Waulsortian Mudbank Complex. These limestones pass up into the Waulsortian itself. There is some mineralization in the area; two small defunct copper mines, probably in vein mineralization, occur near Pallaskenry, and more extensive lead mineralization is present in Lower Carboniferous rocks near Ballysteen to the west.

The full trace element results are presented in Appendix 2 and averages in Table 3 - 4. Of the seven samples of Old Red Sandstone collected,

TABLE 3-4 Pallaskenry-Foynes section (Area 9), summary of results

Zone	Succession	Classification		Pb ppm	Zn ppm	Cu ppm	Ni ppm	Ba ppm	Sr ppm	Rb ppm	As ppm	Mo ppm	Mn ppm	Hg ppb	S %	SiO_2 %	Al_2O_3 %	$CaCO_3$ %	Fe_2O_3 %
C_1	Waulsortian	Waulsortian	n	7	7	7	7	3	2	3	—	—	—	5	—	—	—	—	—
	Bank Complex	Limestone	R	<17-20	<6	<8-14	<8-19	174-206	161-163	<5				<20-39					
			M	<17	<6	~10	~5	187	162	<5				~21					
Z_2	Ballysteen	Limestone	n	12	12	12	12	6	6	6	2	—	2	4	2	2	2 2	2	2
	Limestone		R	<17-28	7-133	<8-23	<8-34	160-262	514-1764	<5-23	26-31		74-124	45-65	0.08-0.13	4.1-27.5	1.2-1.8	66.5-88.8	1.2-2.4
			M	~13	43	~15	~17	223	1015	~14	29		99	57	0.11				1.8
Z_1	Lower	Limestone	n	5	5	5	5	5	5	5	3	4	3	2	3	3	3	3	3
	Limestone		R	<17-26	~6-94	11-18	14-39	160-248	417-1042	<5-7	27-44	<2-2	880-1739	34-214	0.22-0.46	6.7-17.4	1.4-2.9	70.3-80.7	3.2-6.0
	Shales		M	20	44	14	22	217	759	<5	35	<2	1403		0.33				4.6
Z_1	"	Limestone	n	6	6	6	6	5	5	5	4	5	4	3	4	4	4	4	4
		shale	R	<17-44	46-447	21-47	46-83	350-566	81-594	105-270	<25-35	<2-2	272-1072	45-295	0.02-0.13	32.7-64.2	8.2-19.3	0.0-48.0	4.6-5.8
			M	~27	168	31	68	442	310	175	~27	<2	536	179	0.22				5.3
Z_1	"	Shaly	n	4	4	4	4	3	3	3	2	3	2	2	2	2	2	2	2
		Limestone	R	<17-47	~6-107	13-26	23-63	276-380	767-967	49-96	<25-43	<2	664-973	56-150	0.16-0.23	26.7-40.3	6.3-8.7	40.6-59.0	2.8-4.6
			M	~22	58	19	39	331	860	79	~28	<2	819	103	0.20				3.7
K	"	Limestone	n	7	7	7	7	7	7	7	5	6	5	—	5	5	5	5	5
		shale	R	<17-57	33-115	<8-66	35-116	530-880	57-670	107-302	<25-167	<2-6	274-717		0.03-0.11	0.7-64.6	10.5-19.6	0.0-34.0	5.0-7.1
			M	~17	61	~29	65	702	324	201	~56	~2	477		0.07				6.2
K		Shaly	n	3	3	3	3	3	3	3	2	2	2	1	2	2	2	2	2
		limestone	R	<17-46	37-100	<8-29	37-39	348-510	202-927	64-70	<25	<2	470-1126	53	0.05-0.15	9.3-56.1	4.9-9.0	21.0-69.2	2.7-5.7
			M	~32	77	19	38	441	522	67	<25	<2	798		0.10				4.4
K	"	Sandstone	n	1	1	1	1	1	—	—	—	—	—	—	—	—	—	—	—
			R	<15	36	21	62	663											
	Old Red	Sandstone	n	5	5	5	5	5	—	—	—	2	—	—	—	—	—	—	—
	Sandstone		R	<15	<5-22	<7-32	<7-29	179-3358				<2							
			M	<15	~8	~13	~13	7				<2							
	Old Red	Shale	n	2	2	2	2	2	1	1	—	—	—	—	—	—	—	—	—
	Sandstone		R	<17-21	16-24	12-935	94-117	770-1144	2700	283									
			M	~15	20		106	957											

one shale contains anomalous copper (935 ppm), and two samples of sandstone collected 3 m apart on strike contain over 3000 ppm of barium. The presence of vein copper in the area may explain the copper although not necessarily the barium.

The only anomalous concentrations of trace elements in the K_m zone are of arsenic (167 and 65 ppm in a shale and limy shale respectively), and lead up to 57 ppm. An enrichment of zinc (321 and 447 ppm) in a bed low down in Z_1 is presumably primary; the samples represent a bed 5 m thick.

Although not sampled, the top of the Ballysteen Limestones contain disseminated sulphides 2.5 km westsouthwest of Ballysteen (8 km west of Pallaskenry). There may be relatively rich mineralization in the area (pers. comm. Lawlor 1966) and the presence of these sulphides need not indicate a sedimentary enrichment.

Kilmore (Area 9a)

Forty samples were collected from Upper Old Red Sandstone and Lower Carboniferous rocks near Kilmore. The stratigraphy was taken from the one inch to the mile Geological Survey of Ireland map 151, and from Khan (1955). Results are presented in Table 3-5 and Appendix 2. Some samples from the top of the Old Red Sandstone and the bottom of the Lower Carboniferous Limestone Shales at Kilmore are enriched in lead and to some extent in copper and zinc. These results must be seen in the light of the permeability of the beds and the presence of an old lead mine in Old Red Sandstone just north of Causeway village, 4 km south of the sampling sites. The spasmodic occurrence of anomalous concentrations of lead in the Old Red Sandstone would support a theory of deposition of metal from solutions circulating through the sandstones. As the Lower Carboniferous rocks containing relatively high concentrations of lead, zinc and copper are silts, these anomalies may be explained in the same way. If this explanation is correct then a more concentrated deposit could exist in

TABLE 3-5 Kilmore section (Area 9a), summary of results

Zone	Succession	Classification		Pb ppm	Zn ppm	Cu ppm	Ni ppm	Ba ppm	Sr ppm	Rb ppm	As ppm	Mo ppm	Mn ppm	Hg ppm	S %	SiO_2 %	Al_2O_3 %	$CaCO_3$ %	Fe_2O_3 %
S_1	Calp	Limestone	n	3	3	3	3	2	2	2	1	—	1	1		1	1	1	1
			R	<17-23	10-69	27-195	15-75	150-300	196-684	<5	<25		264	37	0.08	41.7	0.9	51.6	0.6
			M	≤17	41	84	40	225	440	<5									
C_1	Waulsortian	Waulsortian	n	5	5	5	5	1	1	1	1	—	1	2	1	1	1	1	1
	Bank Complex	Limestone	R	<17-20	6-~6	<8-12	<8	156	195	<5	<25		<30	33-85	0.02	0.0	0.2	99.2	0.0
			M	<17	<6	~8	<8							59					
KZ	Lower Lime-stone	Silts and shales	n	8	8	8	8	8	5	5	4	—	4	—	5	5	5	5	5
	Shales		R	<15-64	85-360	21-213	52-146	507-950	43-68	127-161	<25-304		600-2952		0.01-0.06	66.2-72.3	13.4-16.2	0.0-2.2	4.0-9.6
			M	~25	190	42	83	667	57	141	~97		1818		0.05				5.7
KZ	"	Limestones	n	4	4	4	4	2	2	1	—	—	—	—	—	—	—	—	—
			R	<17-30	<5-33	<8-14	<8-15	204-244	464-514	8									
			M	~20	~14	~10	≤8	224	489										
	"	Silts and	n	4	4	4	4	4	—	—	—	3	—	—	—	—	—	—	—
		shales	R	<15-503	57-196	<8-92	28-68	393-683				<2-~2							
			M	197	108	~49	50	533				<2							
	Old Red	Sandstone	n	16	16	16	16	16	—	—	—	3	—	2	—	—	—	—	—
	Sandstone		R	<15-735	23-136	<7-340	<7-128	351-1090				<2-4		52-58					
			M		~63	~40	~60	482				~2		55					

the limestones around the Old Red Sandstone inlier.

Kazakhstan Section (Lurye 1957)

In the north of Bayaldyr, Central Kazakhstan, there is a lithological succession broadly similar to that of Ireland. The oldest rocks in the area are folded sandstones and shales of Lower Silurian age. A pronounced unconformity separates the Lower Silurian from 300 m of Middle and Upper Devonian sandstones which are in turn overlain by an Upper Devonian limy shale member 200 m thick. A carbonate sequence 1250 m thick follows; 350 m of which completes the Upper Devonian; the remainder represents the Lower and Upper Carboniferous. The carbonate sequence consists of limestones, dolostones and a few beds of dolomite and some shaly admixtures. Extrusive and intrusive rocks are absent from the region.

A strata-bound lead-zinc deposit occupies part of the Upper Devonian carbonate group at Mirgalimsai, a position in a lithological succession reminiscent of some of the Irish deposits. Twenty kilometres north of this deposit Lurye (1957) collected and analysed spectrographically samples of rock from the sequence outlined above. All samples containing macroscopically discernable mineralization were excluded. Trace element contents of these rocks are unremarkable except for samples of the bottom 500 m of the carbonate sequence. The average trace element contents of the two hundred and sixty four samples from these beds are Pb 370 ppm, Zn 490 ppm (including a 150 m bed, average 1500 ppm), Cu 20 ppm, Ba 50 ppm and Mn 1450 ppm. Trace element contents in the overlying 750 m of carbonates are generally much lower, usually below detection limit excepting manganese and even this element is present in concentrations at or below 300 ppm.

Clearly the zinc and more especially the lead are highly enriched in the lower part of the carbonate sequence; the copper, barium and manganese are also relatively high. The stratigraphic restriction of these elements and their development over a large area (at least 30 km^2)

leads Lurye to conclude that they represent a primary sedimentary accumulation. Moreover, as the Mirgalimsai ores differ from the host rock by the same association of elements, Lurye intimates a sedimentary origin for the Mirgalimsai strata-bound deposit.

Discussion of the Reconnaissance Survey of Rocks from Non-mineralized Areas

There are no syngenetic enrichments of lead and zinc in the sequences of the Irish Carboniferous at a comparable tenor to those in the lower carbonate beds in northern Bayaldyr. Some, presumably primary, minor enrichments do occur. For example, a limestone shale bed (low Z_1) at Pallaskenry is enriched in zinc; and lead and more particularly arsenic are more concentrated in Lower Carboniferous shaly sediments. Barium is generally high throughout the succession though again more concentrated in shaly members. The manganese content is variable but in the Rush section it is particularly high in the C_2S_1 limestones. Other anomalous concentrations of lead, zinc, copper and barium occurring in permeable rocks may have been introduced subsequent to deposition by circulating formation waters.

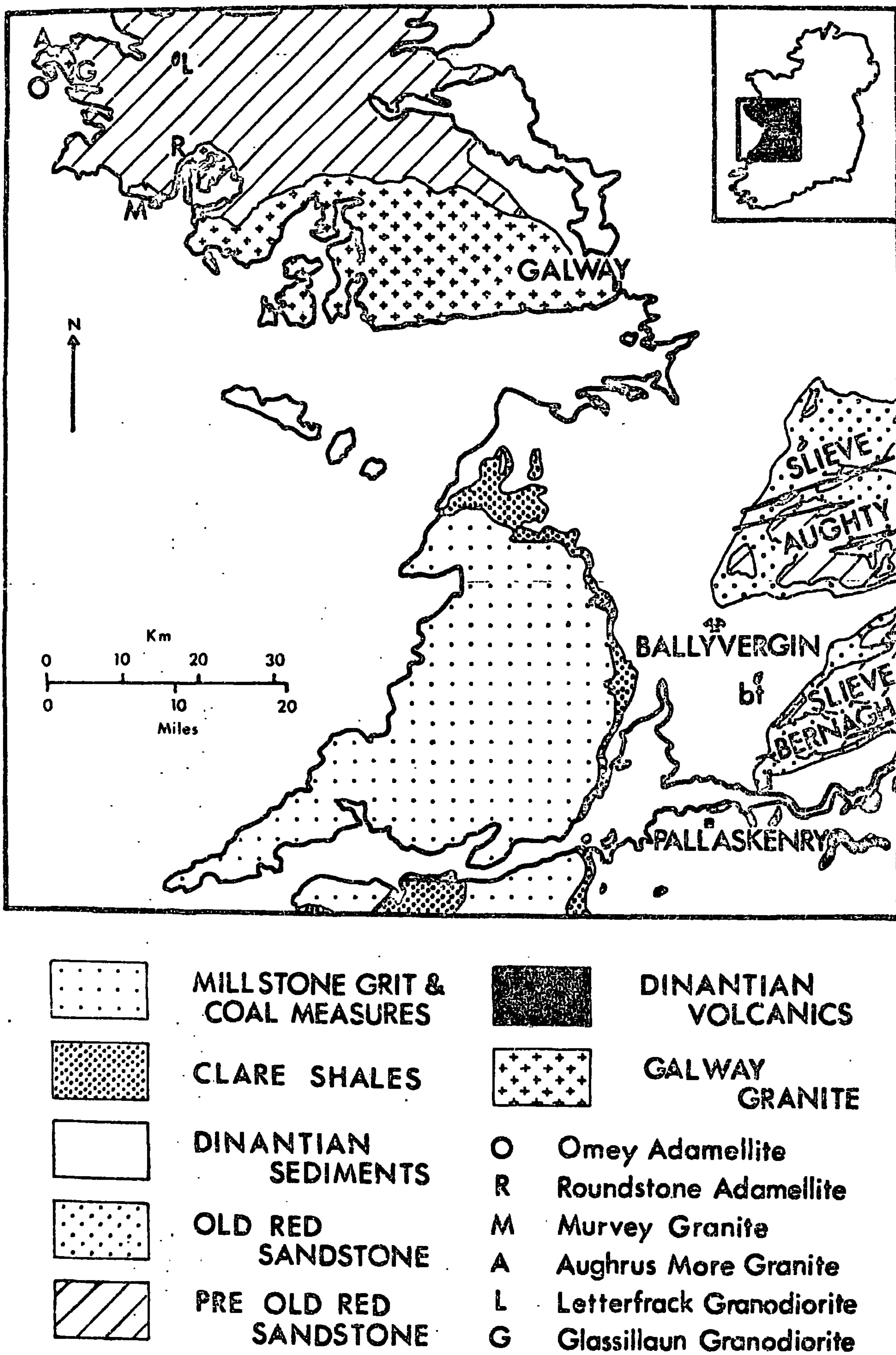
These results leave open the question of whether or not mineralizing solutions disgorged into the Lower Carboniferous sea. The small and stratigraphically restricted enrichments of trace elements could be explained in different ways. For example, arsenic is often found in volcanic gases and hot springs but can also be derived from weathered magmatic rocks. Also the Carboniferous sea was shallow and circulation may have been restricted thus preventing a general enrichment outside of a hot spring area or particular lagoon. Some metals may have been precipitated as carbonates only to have been redissolved during diagenesis.

IV THE ORIGIN OF COPPER AT BALLYVERGIN

Introduction

The Ballyvergin copper mineralization, described by Hallof, Schultz and Bell (1962) as a replacement zone in a domed body of interbedded limestones and shales of lower Tournaisian age, appeared to me a possible example of an essentially sedimentary deposit, subsequently concentrated into a zone of relatively low pressure by local lateral secretion. This idea is similar to Knight's source bed concept (1957) except that the migration of sulphides took place under the influence of differential pressures rather than a rise in temperature. The total geological environment could support such a hypothesis. For instance, some Upper Old Red Sandstone beds in southern Ireland contain concentrations of copper assumed to be syngenetic by Jukes (1861), while the Namurian Clare Shale contains anomalous concentrations of molybdenum (Webb and Atkinson 1965). Just to the north is a possible source for both metals, a large adamellite body, the Galway Granite. Even now this granite contains some molybdenite (O'Brien 1959; Townend 1966) and higher than normal concentrations of copper (Wright 1964; Townend 1966) (Figure 4 - 1). If this Lower Devonian granite and associated mineralization were to have been weathered during Upper Old Red Sandstone times, released cupric ions could have been transported southwards in meandering rivers to be precipitated in shallow lakes and lagoons then in existence in southern Ireland. In the reducing conditions of the Tournaisian seas, the copper might be deposited close to the granite in a concentrated form; Ballyvergin could be but one example of such a deposit. Concluding the postulation, in lower Namurian times a molybdenite deposit in the roof of the Galway batholith was also exposed and molybdenum transported and reconcentrated in the Clare Shales to the south.

Motivated by a predisposition for syngenesis, I determined to



A
G
O
L
R
M
GALWAY
N
SLIEVE
AUGHTY
BALLYVERGIN
bf
SLIEVE
BERNAGH
PALLASKENRY
Km
0 10 20 30
0 10 20
Miles
MILLSTONE GRIT & COAL MEASURES
CLARE SHALES
DINANTIAN SEDIMENTS
OLD RED SANDSTONE
PRE OLD RED SANDSTONE
DINANTIAN VOLCANICS
GALWAY GRANITE
O Omey Adamellite
R Roundstone Adamellite
M Murvey Granite
A Aughrus More Granite
L Letterfrack Granodiorite
G Glassillaun Granodiorite

Figure 4 - 1

Geological environment map to the Ballyvergin copper deposit (from: the Geological Map of Ireland, Brindley and Gill 1958; Schultz and Sevastopulo 1965 and Townend 1966). Capital letters denote granite bodies mentioned in text, bt denotes basaltic tuffs.

analyse the lateral equivalents of the mineralized bed, expecting to find, at least, anomalous concentrations of copper.

Geological Environment

The oldest rocks in the general area belong to the Dalradian, Ordovician and Silurian systems, labelled 'pre-Old Red Sandstone' in Figure 4 - 1. Intruding these rocks in the north is the Galway Granite, a porphyritic adamellite of Lower Devonian age (Leggo and coworkers 1966). In the east it is overlain unconformably by Carboniferous Limestone, but to the west the present level of exposure is close to the granite's gently inclined roof. Several cross-cutting intrusions outcrop. In this western area molybdenite occurs as disseminations and in quartz veins in the Omey and Roundstone Adamellites, and in some concentration along the margin of the Murvey Granite (O'Brien 1959). Several of these intrusions contain higher than normal concentrations of copper, up to 145 ppm in the Aughrus More Granite and an average of 74 ppm in the Letterfrack Granodiorite (Wright 1964; Townend 1966). In the Glassillaum Granodiorite, however, the copper content averages only 25 ppm. Townend (1966) suggests that this difference between the two granodiorites can be better explained by assuming the copper to be in sulphides and not in ferromagnesian minerals, and points out that pyrite is a common accessory mineral at Letterfrack.

Thus it is possible to speculate that disseminated copper and molybdenum deposits occurred near the roof of the Galway batholith which has since been eroded away. Such deposits are commonly associated with adamellites in western North America (Lowell and Guilbert 1970).

The Old Red Sandstone outcropping in Slieve Aughty and Slieve Bernagh comprises alluvial sandstones, siltstones and shales (Hudson and Sevastopulo 1966). The Upper Old Red Sandstone in the south of Ireland is enriched in copper in certain horizons. In early Tournaisian times the seas had transgressed from the south and reached the alluvial plains in the Ballyvergin area. The K_m zone is represented by tidal flat sediments (ibid). Further south at Pallaskenry the sediments are similar, except for a possible lagoonal phase at the base of the Tournaisian succession (Shephard-Thorn 1963). By the time the host rocks to the Ballyvergin copper deposit were laid down in Z_1 times, there was little current activity. It is assumed that these dark calcareous shales with their thin bands of fossils, many of them unbroken, and the interbedded argillaceous limestones were deposited below low tide level (Hudson and Sevastopulo 1966). Overlying these beds is a member comprising greenish-grey laminated siltstones and shales. This is superseded by argillaceous limestones which in turn are overlain by bioclastic limestones. The Waulsortian mudbank complex follows, and the Dinantian closes with dark slightly argillaceous limestones. Volcanic rocks belonging to an alkali basalt differentiation series occur in limestones of C_2S_1 and D_1 age in Counties Limerick and Tipperary. Basaltic tuffs of D_1 age have recently been discovered ten kilometres southeast of Ballyvergin (bt in Figure 4 - 1). (Schultz and Sevastopulo 1965). There was a non-sequence at the base of the Namurian and then the Clare Shales were laid down under marine conditions. Analysis of these shales by Webb and Atkinson (1965) show that they contain molybdenum ranging from 5 to 150 ppm and selenium from 5 to 30 ppm.

Both elements are present in highly anomalous quantities. It is interesting to note that Goldschmidt (1958) found that molybdenite from Knaben, Norway, contains 180 ppm selenium. It is possible then that the molybdenum in the Clare Shales was derived from a molybdenite occurrence weathered out from near the roof of the Galway batholith, although it must be said that black shales are often enriched in molybdenum even where an obvious local source is not available.

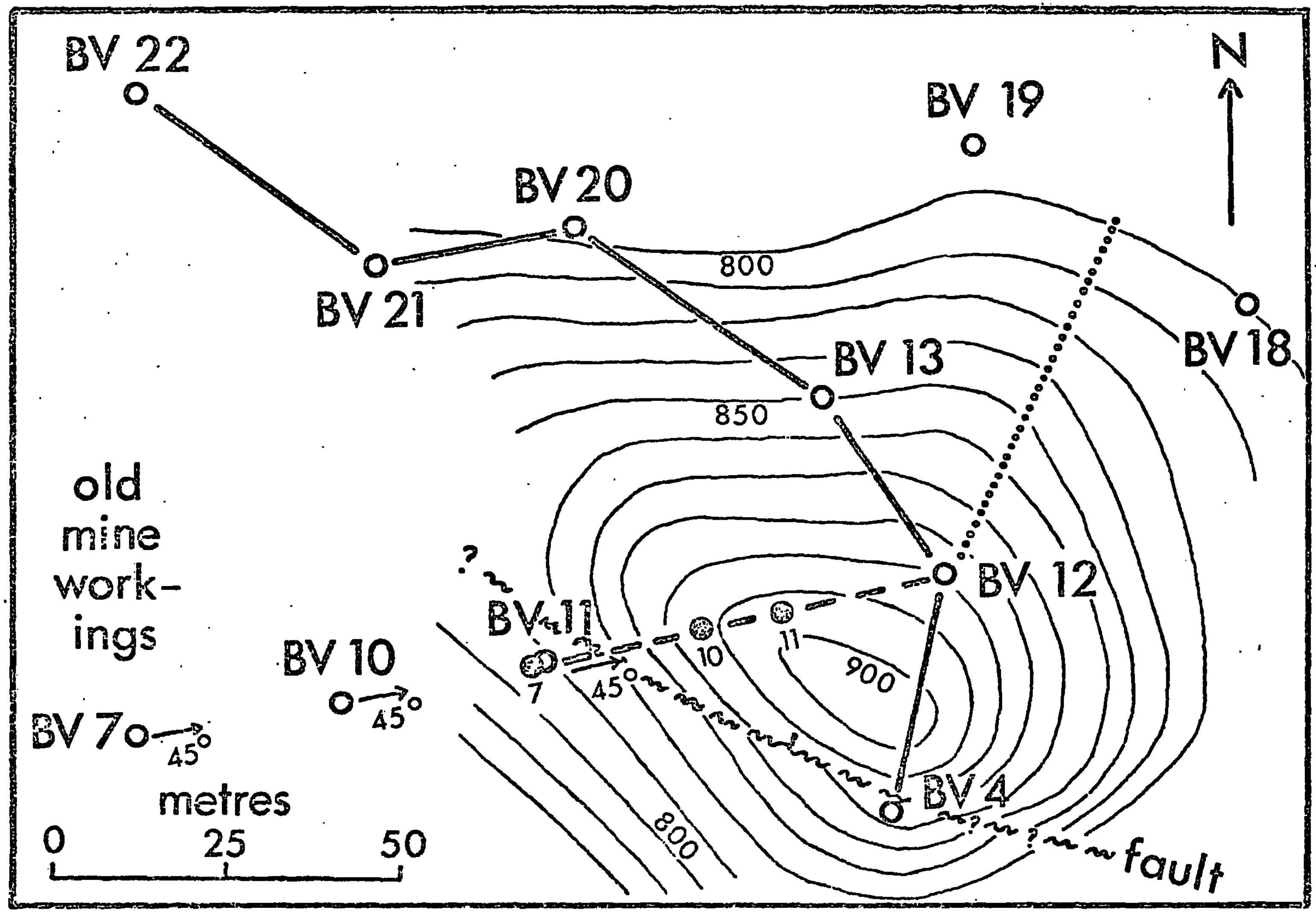
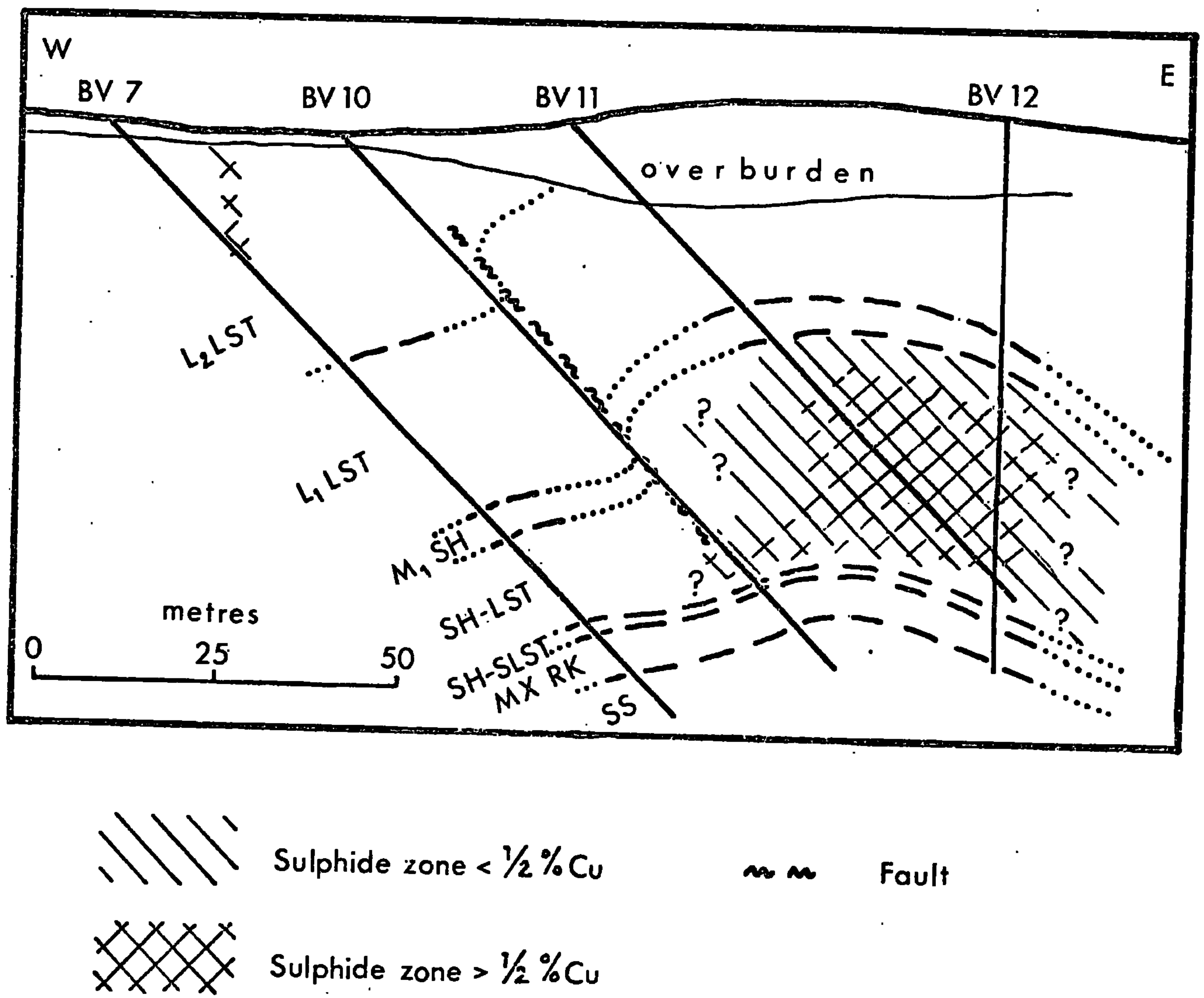

N
BV 22
BV 19
BV 20
BV 21
800
BV 18
BV 13
850
old mine workings
BV 12
BV 11
10
11
900
7
45
BV 10
45°
BV 7
45°
BV 4
metres
0
25
50
800
fault

Figure 4 - 2

Plan of drill holes sampled for analysis. Filled circles denote the intersections of holes drilled at 45° with the midpoint in the argillaceous limestone SH-LST. Uninterrupted line denotes section used in Figure 4 - 6. Broken and dotted line is section used in Figure 4 - 7. Structure contour pattern of the M_1 shale is shown (contour interval equals 10 feet (3.05 m)). Tick on reverse fault is to superposed side. (Redrawn from unpublished diagrams kindly provided by RW Schultz).



W
E
BV 7
BV 10
BV 11
BV 12
overburden
L2LST
L1LST
M1SH
SH-LST
SH-SLST
MX RK
SS
metres
0
25
50
Sulphide zone < ½ %Cu
Sulphide zone > ½ %Cu
Fault

Figure 4 - 3

Drill hole section through the mineralized dome at Ballyvergin (redrawn from Hallof, Schultz and Bell 1962).

L_2LST, slightly argillaceous bioclastic (mainly crinoidal) limestone;

L_1LST, argillaceous bioclastic limestone and interbedded shale;

M_1 SH, laminated shale and siltstone;

SH-LST, shale and argillaceous limestone;

SH-SLST, banded shale and stilstone;

MX RK, mixed rock: shale, siltstone, sandstone and minor limestone;

SS, predominently sandstone, underlain by Old Red Sandstone shales and siltstones;

Scattered sulphide mineralization (mainly chalcopyrite) intersected in drill holes BV 7, BV 10 and BV 11 above M_1SH.

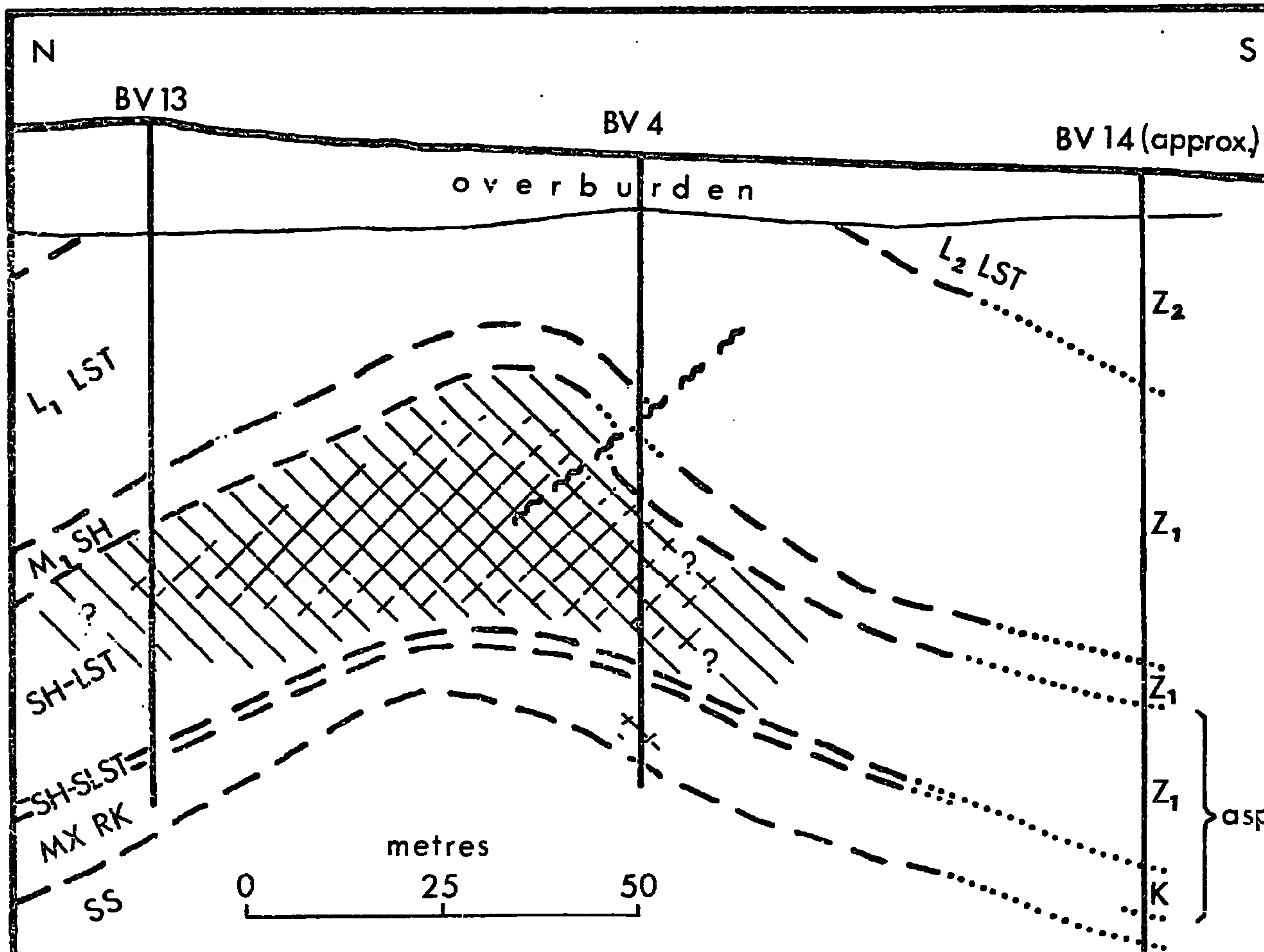

N
S
BV 13
BV 4
BV 14 (approx.)
overburden
L_2 LST
L_1 LST
Z_2
Z_1
Z_1
Z_1
K
asp
M_1 SH
SH-LST
SH-SLST
MX RK
SS
metres
0
25
50

Figure 4 - 4

Drill hole section through the mineralized dome at Ballyvergin with the approximate zonal boundaries drawn from faunal evidence in BV 14 by Hudson and Sevastopulo 1966: asp denotes minor arsenopyrite; other abbreviations as for Figure 4 - 3. (Redrawn from an unpublished diagram kindly provided by RW Schultz).

The remainder of the Upper Carboniferous rocks in County Clare comprise sandstones and shales.

Mineralization

Numerous calcite veins containing galena and other sulphides traverse the Carboniferous Limestone in parts of County Clare (Cole 1922). At Ballyvergin itself a small lode containing chalcopyrite and galena in a gangue of coarse calcite was mined in the middle of the last century. The form of the mineralization at the newly discovered copper deposit at Ballyvergin is quite different. This has been described by Hallof, Schultz and Bell (1962) and the account that follows is taken from their work.

The copper occurs mainly as chalcopyrite disseminated in limy shales at the base of the Lower Limestone Group. The chalcopyrite partly or completely replaces calcareous fossils and fossil fragments, and also occurs in discrete flecks often parallel to the bedding, and occasionally in crosscutting, centimetre-scale, gash veinlets. It is notable that pure, non-argillaceous limestone and pure non-calcareous shale are generally only weakly mineralized. The mineralized bed is from fifteen to over thirty metres thick, the increase in thickness marking the centre of a disharmonically folded, elongated dome in which mineralization is concentrated (Figures 4 - 2, 4 - 3, 4 - 4). According to a faunal study of a drill hole from Ballyvergin (BV 14, Figure 4 - 3), by Hudson and Sevastopulo (1966), the mineralized bed belongs to the bottom of the Z_1 zone of the lower Tournaisian. Drilling indicates reserves of at least 150,000 tonnes of ore, grading 1.2% copper and 14 gm silver per tonne. Overlying the host limestone shale member is a bed of dense, shaly mudstone about five metres thick.

The chalcopyrite zone appears to be enveloped by an arsenopyrite fringe, and sparse galena and pyrite occur in veinlets in limestones overlying the stratabound deposit, especially over the western flank in the vicinity of a minor reverse fault. One hundred metres to the west is the Old Ballyvergin mine which worked the irregular lode in crinoidal limestone.

Hallof and coworkers (1962) tentatively ascribe the origin and control of the mineralization to post-folding deposition from ascending hydrothermal solutions.

More recently, Brown (1969) has studied the lithology, structure and mineralization of the related areas of Ballyvergin and Maghera Cross (2.5 km eastsoutheast from Ballyvergin) and believes the vein mineralization to be of secondary local derivation from the concordant mineralized zones. This latter type of mineralization, he suggests, originated from upward migrating metal-rich epigenetic fluids.

Methodology and Assumptions

> "The source bed concept postulates that all sulfide ore bodies of the majority of fields are derived from sulfides that were deposited syngenetically at one particular horizon of the sedimentary basin constituting the field, and that the sulfides subsequently migrated in varying degree under the influence of rise in temperature of the rock environment." (Knight 1957).

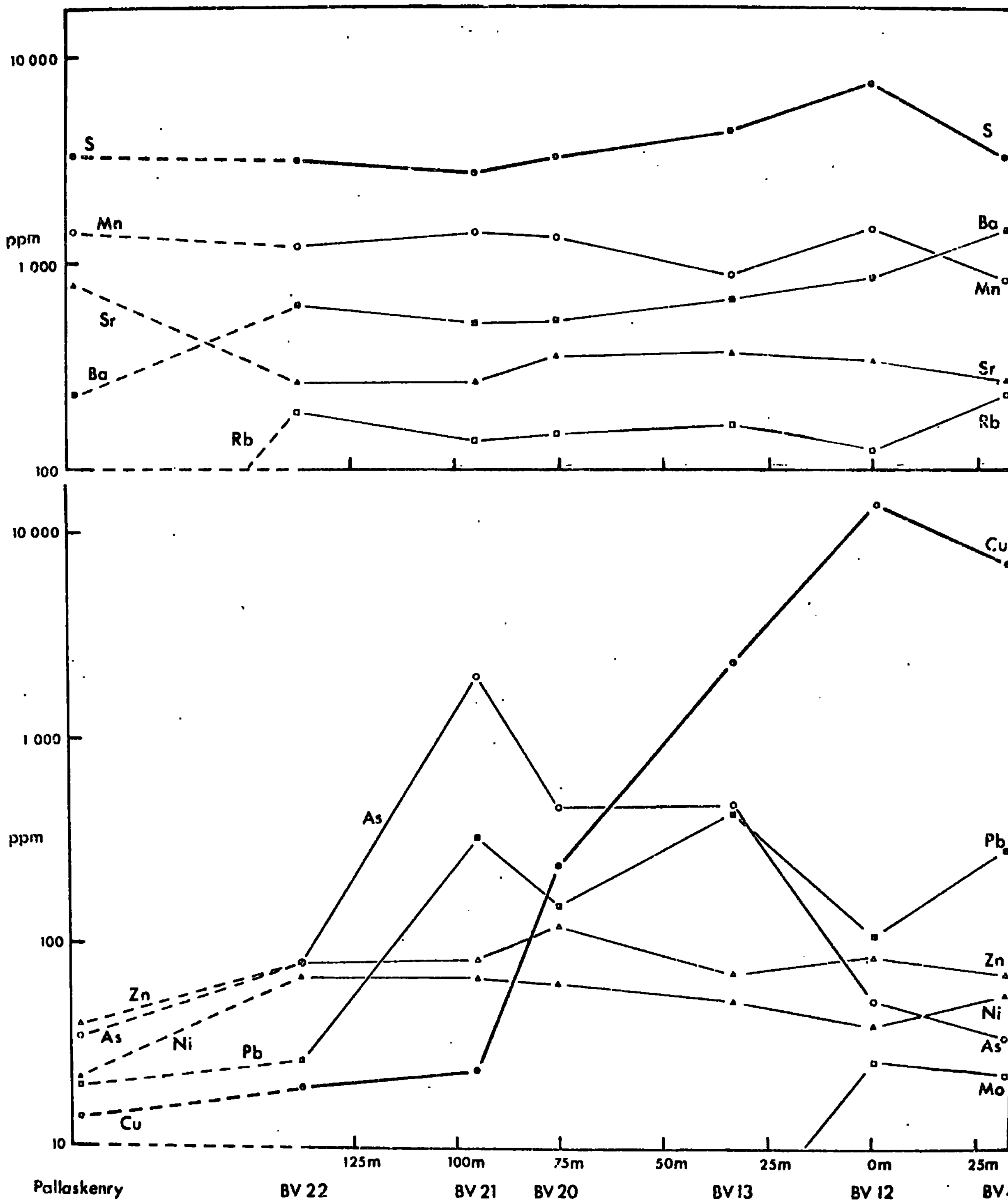
The purpose of this study was to test a modified source bed theory for the Ballyvergin deposit, in which syngenetic sulphides migrated down a pressure gradient into the dome. For such a theory to be acceptable, it must be shown that the mineralized horizon contains anomalous concentrations of metals at a distance from the mineralization itself. Hirst and Dunham (1963), analysing the English Marl Slate, the lateral equivalent of the German Kupferschiefer, found abnormal contents of zinc, lead and copper, thus supporting the sedimentary theory for the origin of the metals in the shale. Employing a similar method of investigation, I analysed samples from both close to, and remote from, the deposit at Ballyvergin.

Hirst and Dunham (ibid) found the concentration of copper in the Marl Slate to range from 13 to 754 ppm. If a few hundred parts per million copper were found in the host rocks outside of any possible epigenetic aureole to the Ballyvergin deposit, and this content increase towards the deposit, then a syngenetic factor could be assumed. It is possible, however, to argue that the surrounding rocks would be depleted in the ore metals by such lateral secretion. If so then we might expect to see visual evidence of this in that diagenetic sulphides may show signs of alteration. If lateral beds some distance from the deposit are enriched in the ore metals then a source bed theory could still be argued.

The assumptions made in a study of this kind have an interesting history. Sandberger discovered traces of heavy metals in the wall rocks to ore shoots occurring in Central Europe, and this led him to propose his lateral secretion theory in 1885. Sandberger's definition of this theory as translated by RW Raymond in Pošepný's paper on the genesis of ore deposits (1894) is,

> "The theory of lateral secretion was conceived in this sense only, that the material for the filling of veins is derived from country rock through gradual leaching by seepage water (Sickerwasser), which brings the dissolved substance from both sides to the vein-fissure, where it is then converted by chemical decompositions into insoluble gangue minerals and ores, and so deposited."

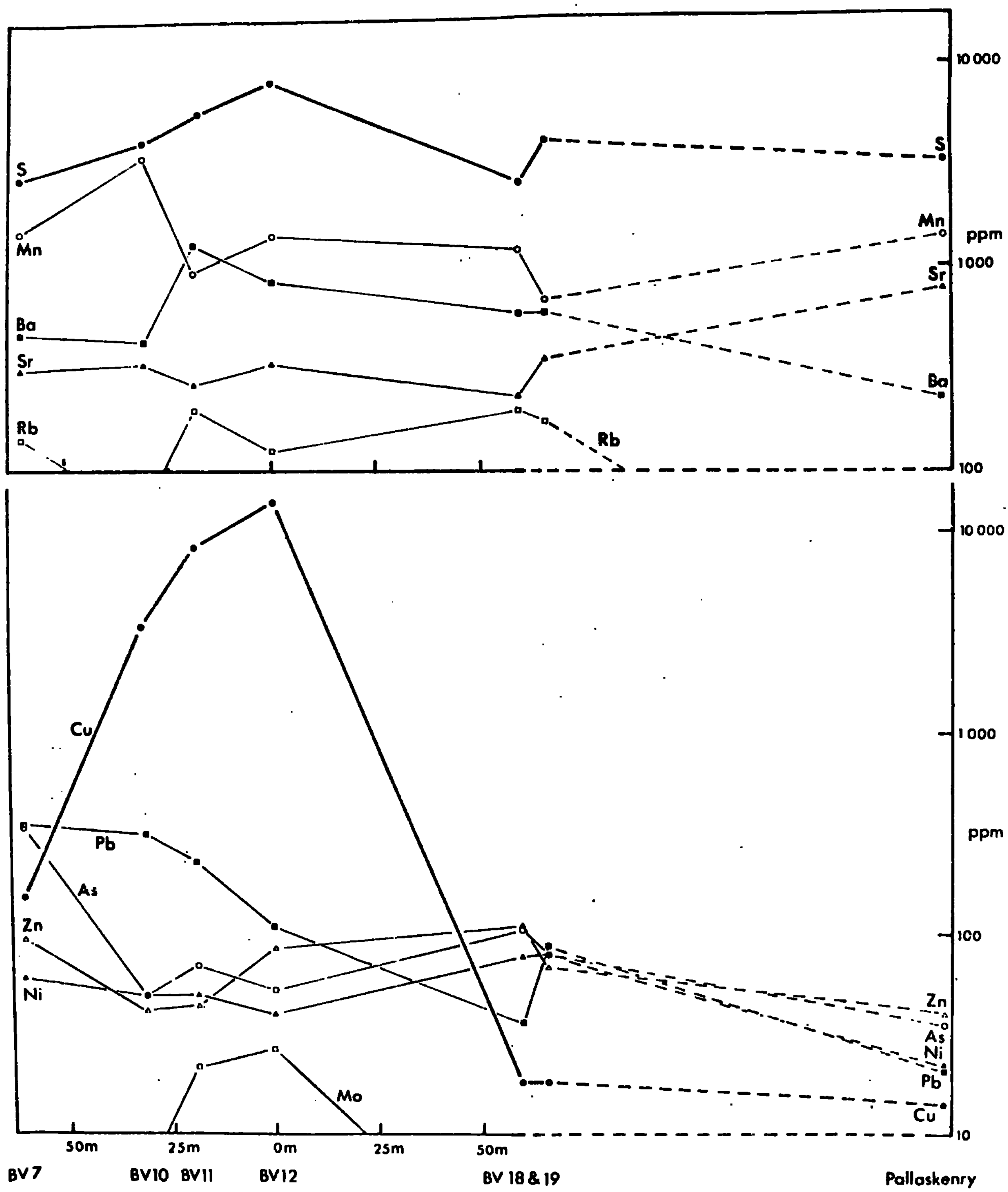
Pošepný (1894) argued strongly against this thesis, suggesting that such a theory could only hold above ground water level because only there are fissures open. This part of the argument centred on the word 'Sickerwasser'. Emmons (1894) felt that Pošepný had interpreted the



10 000
ppm
1 000
100
S
Mn
Sr
Ba
Rb
Cu
As
Pb
Zn
Ni
Mo
10
125m
100m
75m
50m
25m
0m
25m
Pallaskenry
BV 22
BV 21
BV 20
BV 13
BV 12
BV 4

Figure 4 - 5

Trace element distribution pattern in SH-LST, Ballyvergin copper deposit, and a comparison with concentrations in more limy rocks at Pallaskenry. Sulphur results are semi-quantitative.



S
Mn
Ba
Sr
Rb
10 000
ppm
1000
100
Cu
Pb
As
Zn
Ni
Mo
10 000
1 000
ppm
100
10
50m
25m
0m
25m
50m
BV7
BV10
BV11
BV12
BV 18 & 19
Pallaskenry

Figure 4 - 6

Trace element distribution pattern in SH-LST, Ballyvergin copper deposit, and a comparison with concentrations in more limy rocks at Pallaskenry. Sulphur results are semi-quantitative.

lateral secretion theory too narrowly and argued that the theory implied derivation of vein content from rocks within a reasonable proximity as opposed to a source at unknown depths. Therefore the theory could include upward, downward and lateral motion according to differing structural conditions.

Pošepný (1894) calculated that for the Przibram ores to have been derived from the adjacent igneous rocks as suggested by Sandberger, there must have been in each cubic metre 1.9 - 6.3 kg of metallic ingredient. If it is assumed that these rocks contained the largest amount of metal ever recorded for such rocks the igneous formation would have to be one hundred times thicker than it is to provide the metals. Sandberger's assertion that evidence for his theory was to be found in traces of heavy metals in the wallrocks of ore deposits led Stelzner (1889) to investigate the problem analytically. He demonstrated that Sandberger's chemical method (1887) was not capable of decisively determining whether the metals detected in the wallrocks were original constituents, or secondary impregnations. In other words the anomalous heavy metal content could really have been derived from the ore deposit itself.

It is now accepted that where the metal content decreases approximately logarithmically to background a short distance away from the ore contact then the mineralization was epigenetic (Morris 1952 ; Ineson 1969).

Trace Element Results

At least four samples were collected at random from each drill hole section through the shale and argillaceous limestone member SH - LST (see Figure 4 - 3) in the wall rocks and two samples from the mineral deposit sections. The trace element results have been averaged for each drill hole (Appendix 3) and are presented graphically in Figures 4 - 5 and 4 - 6. Of the fifteen samples collected from Pallaskenry and reported in the last chapter, it is clear from the analysis that only nine contain comparable amounts of calcium carbonate and clay. Their

Plate 2

1 Pyrite framboids being pseudomorphed by lepidocrocite or goethite, Pallaskenry.

Reflected light x 500

2 Chalcopyrite replacing bryozoan, Ballyvergin BV 11.

Reflected light x 15

3 Arsenopyrite apparently replacing pyrite framboids, Ballyvergin BV 21.

Reflected light x 100

4 Pyrite cubes replacing pyrite framboids. Some of the framboids are 'streaked out' and are apparently becoming dispersed, Ballyvergin BV 13.

Reflected light x 500

sulphur content, however, is relatively low and a polished section study showed them to be partially oxidised (see Plate 2). The remaining six contain considerably less clay but their sulphur content is similar to that in background samples at Ballyvergin. Any differences in the average trace element concentrations between these last two groups can be explained in terms of their respective lithologies. Analyses of both the weathered and unweathered rocks from Pallaskenry are included in Appendix 3, but only the latter are used in the graphical presentation.

Figures 4 - 5 and 4 - 6 show the copper concentration to rise steeply from background over a distance of 100 m or less. In drill holes BV 18, 19, 21 and 22 copper averages 18, 18, 24 and 20 ppm respectively which compares with the 14 and 28 ppm average copper contents of the Pallaskenry limestones and weathered argillaceous limestones respectively. The arsenopyrite envelope recognised by Hallof and co-workers (1962) gives rise to an arsenic high at the edge of the copper deposit; similarly lead is concentrated in this region but is also enriched throughout the deposit. Molybdenum and barium are enriched in the body of the deposit and sulphur is enriched in the copper zone. Zinc and nickel are not present in anomalous concentrations. The range of concentrations of the major elements and some of the minor elements such as rudibium, strontium and manganese, preclude judgement regarding other possible migrations and additions, excepting a small depletion of iron in one sample from each of drill holes BV4 and BV12.

Petrography

Thirty four polished and thin sections of ore and host rock were studied in order to correlate the geochemical results with the mineralogy. All the polished sections examined from drill holes surrounding the deposit contain abundant framboidal pyrite spheres measuring from 6μ to 10μ, and lesser numbers with sizes up to 30μ. Some of the framboids have been replaced by single crystals of pyrite (Plate 2). Pyrite framboids in the copper deposit itself are often deformed and are apparently becoming dispersed (Plate 2), and in samples from drill holes BV 4 and BV 10, framboids are completely absent. The framboids are remarkably resistant to direct replacement by the chalcopyrite, although the latter is occasionally observed corroding the pyrite spheres and, a little more commonly, replacing pyrite crystals. But, as pointed out by Hallof and coworkers (1962) and Brown (1969), the chalcopyrite occurs mainly as partial replacements of fossils (Plate 2), as disseminations parallel to the bedding, and associated with veinlets. At Pallaskenry framboids up to 40μ in diameter are common. The more shaly samples contain framboids partly pseudomorphed by lepidocrocite or goethite (Plate 2).

Galena occurs on the margins of the deposit partially replacing fossils. The arsenic envelope consists mainly of arsenopyrite grains measuring from 5μ to 50μ. The shape of the grains, and also the fact that they often contain cores of pyrite, implies that they have partially replaced and surrounded pyrite framboids (Plate 2). Larger crystals of arsenopyrite also occur.

All the base-metals in the aureole are apparently combined in sulphides.

Discussion and Conclusions

There are no anomalous concentrations of copper in the argillaceous limestones at Pallaskenry such as would support a local source bed hypothesis for the formation of the Ballyvergin copper deposit. Nor is there a suggestion of a loss of copper in the same beds very close to the deposit. On the contrary, the steep decrease in copper content in the 'wall rocks' to background in less than 100 m favours an epigenetic theory. Moreover the zoning is exactly what we would expect from hydrothermal fluids emanating from near the centre of the dome in the general area of drillholes BV 12, 11 and 4 (cf Taylor 1965). Molybdenum is only concentrated in the centre of the deposit, copper is enriched over a relatively wide area, and lead, although high in the copper body apparently also forms a zone surrounding the deposit. Regarding non-metal enrichments, sulphur is high in the deposit and this is replaced outwards by an arsenic fringe. If lateral secretion were a tenable hypothesis movement and concentration of some zinc into the ore zone could be expected and yet zinc concentration remains reasonably constant from non-mineralized to mineralized sediments.

These findings are similar to those of Barnes (1959) who demonstrated that it was not possible to explain a particular contact metamorphic, a vein type or a Mississippi type ore deposit by lateral secretion of trace elements from adjacent black shales.

The paucity of framboids in the body of the deposit is probably a result of their dissolution in the mineralizing fluids. Some of this sulphur and iron may have taken part in the formation of chalcopyrite or perhaps reconstituted to form the pyrite disseminations in veinlets above the deposit. The fact that pyrite framboids are well preserved in the host rocks just outside the zone of mineralization also argues against a theory of local lateral secretion.

Mimetic replacement of fossils coupled with insignificant strontium depletion argues for a low temperature of sulphide deposition. Ineson (1969) points out that strontium depletion has taken place near veins in the Alston area, England, where the temperature of the mineralizing fluids ranged from 120^{o}C to 170^{o}C, but not in Derbyshire where the temperatures were 85^{o}C to 95^{o}C.

One structural control is clearly the dome, and the shape and situation of the sulphide zone is reminiscent of an accumulation of oil in a similar structural setting. Presumably doming caused an increase of permeability and porosity in the argillaceous limestone, allowing ore bearing fluids to pervade these beds. The position of the conduit (or conduits) is unknown although it is presumably near the molybdenum high. Hallof and coworkers (1962), however, have remarked a weak extension of an Induced Potential anomaly associated with the deposit, running north and south, which they suggest may indicate a weakly mineralized fracture, perhaps another feature of control.

Although a strict source bed concept for the origin of the mineralization is ruled out by these findings, several related theories are still permissible apart from a mantle origin. It is conceivable that the subsidence of the Namurian basins to the west with concomittant compaction of sediment would have caused flow of formation waters towards basement highs. The Upper Old Red Sandstone lay at a depth of up to 1000 m in the synclines to the west. Copper, arsenic and lead could have been leached out of the Upper Old Red Sandstone (and perhaps the lowest Carboniferous) and carried in formation waters through these sandstones, towards a basement high, in a manner similar to that suggested by Noble (1963) for Mississippi type deposits. If we assume a thickness of 100 m for the Upper Old Red Sandstone and an isosceles triangular shaped source with its apex at Ballyvergin and base to the west under a Namurian basin measuring 30 km x 15 km, and a specific gravity of 2.69 (Murphy 1960), then 0.033 ppm of copper leached from this volume would give the 2000 tonnes of copper at Ballyvergin. Even if the total amount of copper at Ballyvergin is 6000 tonnes then still only 0.1 ppm of leached copper is necessary. It is not possible to estimate an original copper content of the Upper Old Red Sandstone in the postulated source area because of redistribution and other changes in this permeable and porous rock. However, it is probable that only a few percent or less of original content would have been required even assuming an inefficient ore forming system.

Whatever the source, the precipitation of the metals in a dome under what appears to be a perfect 'cap rock' makes a theory involving the mixing of mineralizing fluids with 'sour gas' (gas containing H_2S, see Beales and Jackson 1966), most attractive.

The only positive conclusions to be drawn from the results presented here is that the mineralization is neither syngenetic nor the result of local lateral secretion, and that exploration programmes based on the syngenetic-diagenetic model proposed at the beginning of this chapter are unlikely to succeed.

V MINERALIZATION AT GORTDRUM, OOLA AND CARRICKITTLE

Introduction

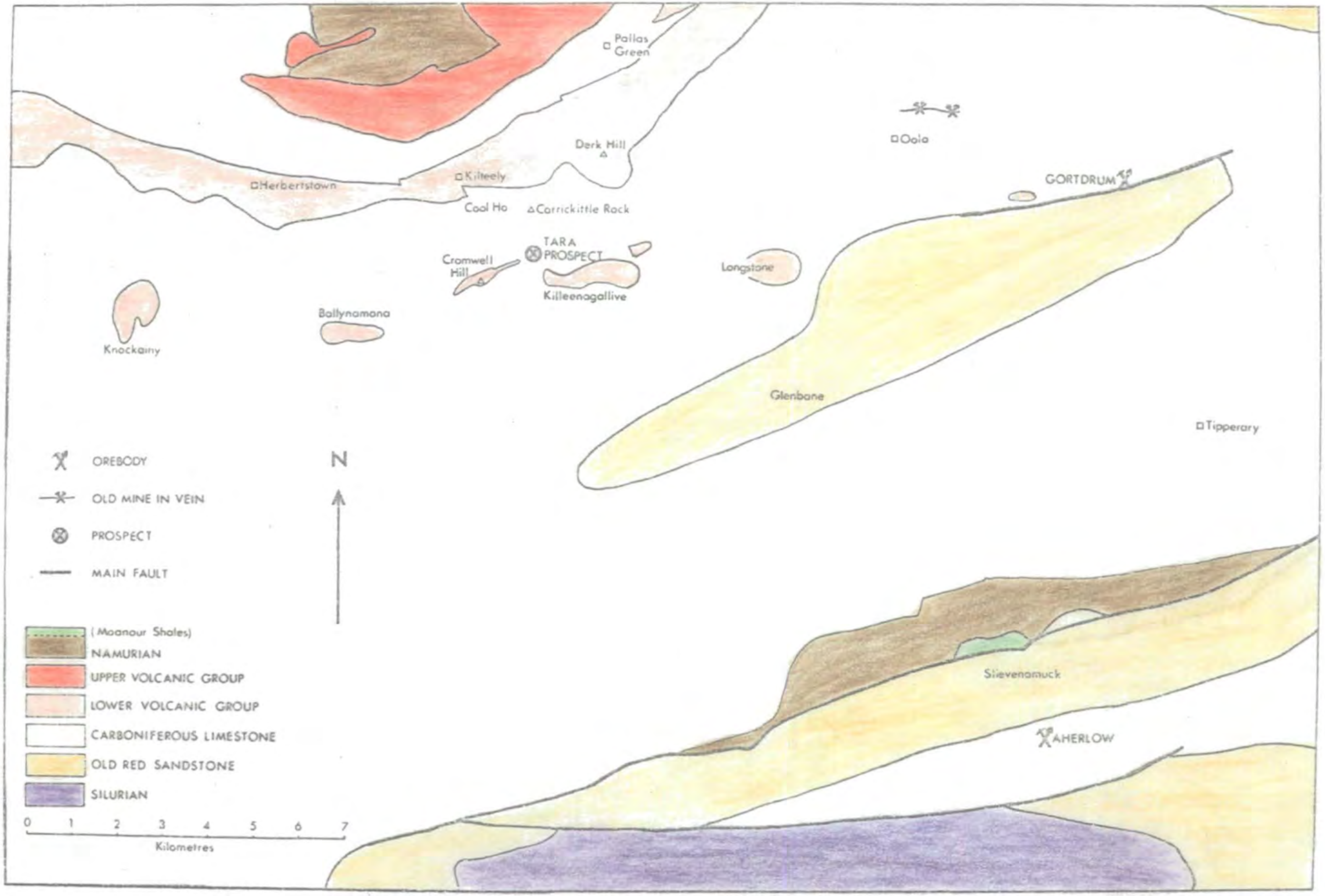
The only mineralization known in this region previous to the recent discoveries was that in an east-west trending shear zone at Oola, (Figure 5 - 1 and 5 - 5) (O'Brien 1959). A mine was in operation in the last century in this zone of argentiferous galena and chalcopyrite, so it is not surprising that a reinvestigation of the area was made. Thompson (1967) records how the Lower Limestone Syndicate secured prospecting area No. 68 which covered the postulated eastern strike extension of the Oola Mine. This prospecting area was subsequently extended southwards and the Gortdrum copper-silver (mercury) deposit was discovered 5 km eastsoutheast of Oola.

A small lead-zinc deposit was also discovered near Carrickittle 13 km to the west of Gortdrum by Brian Byrne of Tara Exploration, on the premise that a genetic relationship existed between the Limerick volcanics and the mineralization in the area (Figure 5 - 1).

My own predisposition also was towards a genetic link between all the deposits and the local igneous rocks, the more so as dyke rocks had been discovered in all three of the mineralized zones. Thus the precise mode of deposition was not so important to me and I had a relatively open mind on that side of the problem, although a source bed origin was considered.

Geological Environment

Folded sediments of Silurian age are the oldest rocks in the area and are seen in the Slievefelim Mountains to the north of Gortdrum. Yellow and purple sandstones belonging to the Old Red Sandstone System overlie Silurian rocks with pronounced unconformity and also form an inlier at Glenbane to the south of Gortdrum. The Old Red Sandstone is succeeded by the marine Lower Limestone Shales of Tournaisian (K-Z_2) age (Ashby 1939). Well bedded pale limestones (Z_2) follow,



Pallas Green
Oola
Derk Hill
GORTDRUM
Kilteely
Herbertstown
Cool Ho
Corrickittle Rock
TARA PROSPECT
Cromwell Hill
Killeenagallive
Longstone
Ballynamona
Knockainy
Glenbane
Tipperary
N
OREBODY
OLD MINE IN VEIN
PROSPECT
MAIN FAULT
(Moanour Shales)
NAMURIAN
UPPER VOLCANIC GROUP
LOWER VOLCANIC GROUP
CARBONIFEROUS LIMESTONE
OLD RED SANDSTONE
SILURIAN
0 1 2 3 4 5 6 7
Kilometres
Slievenamuck
AHERLOW

Figure 5 - 1

Geological map of the Gortdrum-Oola-Carrickittle-Aherlow area copied from the Geological Survey 1" map sheet 154 (Tipperary); and maps from Ashby 1939, Shelford 1963 and Thompson 1967. Note that a narrow belt of intrusives of lower Viséan age appear to be associated with the Gortdrum Fault and its westerly extrapolation, thus implying a mid-Dinantian or earlier age for this structure.

often containing shale partings. The Waulsortian mud bank complex of C age overlies these beds (Plate 1), near the top of which some well bedded limestones are locally interstratified, as also is chert. The base of S_1 is represented by a cherty argillaceous limestone, deposition of which was interrupted by the eruption of basaltic tuffs and lavas from a number of small vents such as Derk Hill and Kilteely Hill. These volcanics belong to an alkaline differentiation series similar to those being erupted in the Midland Valley of Scotland at about the same time. Quartz trachyte sills located to the south of the area may also belong to this period of igneous activity. These sills are intruded into Z_2 limestones and outcrop at Cromwell Hill, Killeenagalive and Longstone. Similar rocks also outcrop to the west at Knockainy and Ballynamona (Figure 5 - 1). Ashby (1939) points out that little of the original mineralogical character is now preserved and doubts whether the quartz was a primary constituent. Altered rocks probably of a similar type are found in the mine areas in the form of dykes, as well as sills.

Following this (lower) volcanic episode, limestone deposition reasserted itself from S_1 to early D_1 times; well bedded foetid limestones give way to lighter, sometimes oolitic limestones higher in the succession. Volcanic activity broke out again in D_1 times, picrite basalts and tuffs being the main representatives. Ashby (1939) concludes that these effusions originated from the direction of Pallas Green (Figure 5 - 1). The upper D_1 sediments consist of yellowish, dolomitic limestones with some volcanic detritus. These are followed by pale D_2 limestones, in turn succeeded by the Pendleside Shales and Millstone Grit.

Methodology

The same type of lithogeochemical survey as that used at Ballyvergin was employed in the investigation of these three mineralized zones. It was hoped that such a survey would have the power to support or refute the hypotheses built on the supposition of some sedimentary contribution to ore deposition. A few samples of Lower Limerick Tuffs were also analysed to test for any base-metal enrichment.

The Limerick Volcanics

A reconnaissance investigation of igneous rocks near Pallas Green was made in order to attempt to establish whether or not a genetic link existed between them and the three mineralized areas to the southeast of this region (Figure 5 - 1).

The investigated rocks were those constituting trachytic sill-like bodies intruded into Z_2 limestones. Ashby (1939) believes that they are related to the first phase of igneous activity of S_1 age, but, as mentioned above, doubts if the original mineralogy is still preserved. Certainly thin sections examined by this writer betrayed staining and some alteration of orthoclass laths, alteration of some plagioclase phenocrysts, the presence of chlorite and hematite and patches of calcite. The quartz appeared fresh but patchily distributed and as suggested by Ashby (1939) was probably secondary.

The sills outcrop in an east-west line and are probably related to dykes and sills encountered in drilling at all three of the mineral deposits. In fact, as noted above, the Carrickittle deposit near Kilteely was discovered on the premise that a link between mineralization and the igneous complex might exist. Thompson (1967) had also suggested that after mid-Carboniferous folding and faulting had produced high porosity in the Gortdrum region, hydrothermal solutions from the west with a probable common origin to the dykes were introduced along fault planes.

Sampling and Analysis of Limerick Volcanics

Eight samples of the sills were collected and analysed for major and trace elements (117-119, 126-129 and CP).

Other igneous rocks analysed were the Lower Limerick volcanic tuffs and lavas collected from Quirkes Quarry (120-123) at a point just northeast of Herbestown (124). An Upper Limerick volcanic (125) collected from near Pallas Green (See Figure 5 - 1), and another collected by KC Dunham (ULV) from an unknown location were also analysed.

Results of Limerick Volcanic Analyses (Appendix 3)

The chemical analyses of the sills show them to be trachytes with no surprising features either in their major or trace element compositions excepting sample 127 which has a high calcium content, due to the presence of calcite found in the thin section. It is true that the Killeenagalive sample (128) is a little high in zinc and nickel but many more analyses would be required in order to establish this as a significantly high level of concentration.

The Lower Limerick volcanic tuffs do not contain an unusual quantity of the analysed trace elements so there is no support for syngenetic enrichment of base metals associated with the volcanism. This does not rule out such a hypothesis for other parts of the same volcanic pile. One major constituent that is well represented is titania, which in these rocks ranges between 2.5% and 3.0%. This may be due to some reworking of these basic tuffs on the sea floor. The only lava analysed was a typical trachyte. The Upper Limerick basic volcanics (ULV and 125) also contain about 3% titania.

Mineralization at Gortdrum

The description of this deposit is taken from Thompson (1967). Mineralization occurs as disseminations and in irregular veins and alteration zones in the Lower Limestone Shale and Lower Limestone (Figure 5 - 3). The main body of the mineralization lies adjacent to the Gortdrum Fault, although at the lower grade margins mineralization sometimes appears to parallel the bedding. The main minerals are bornite,

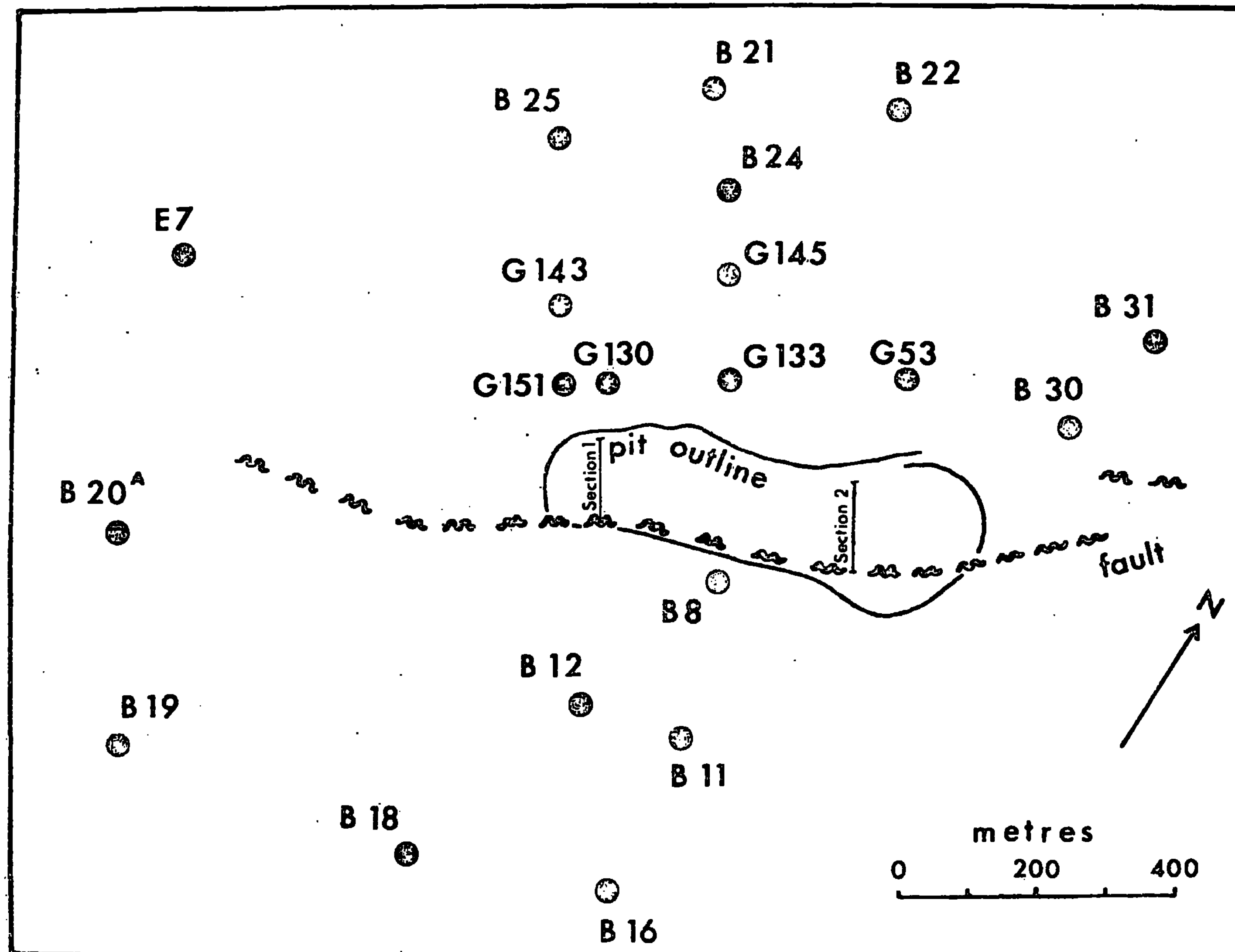

B 21
B 22
B 25
B 24
E7
G 143
G145
B 31
G130
G 133
G53
G151
B 30
pit outline
Section 1
Section 2
B 20A
fault
B 8
N
B 12
B 19
B 11
B 18
metres
0
200
400
B 16

Figure 5 - 2

Plan of the Gortdrum pit, with numbers of the drill holes sampled.
(Plan provided by Gortdrum Mines Limited).

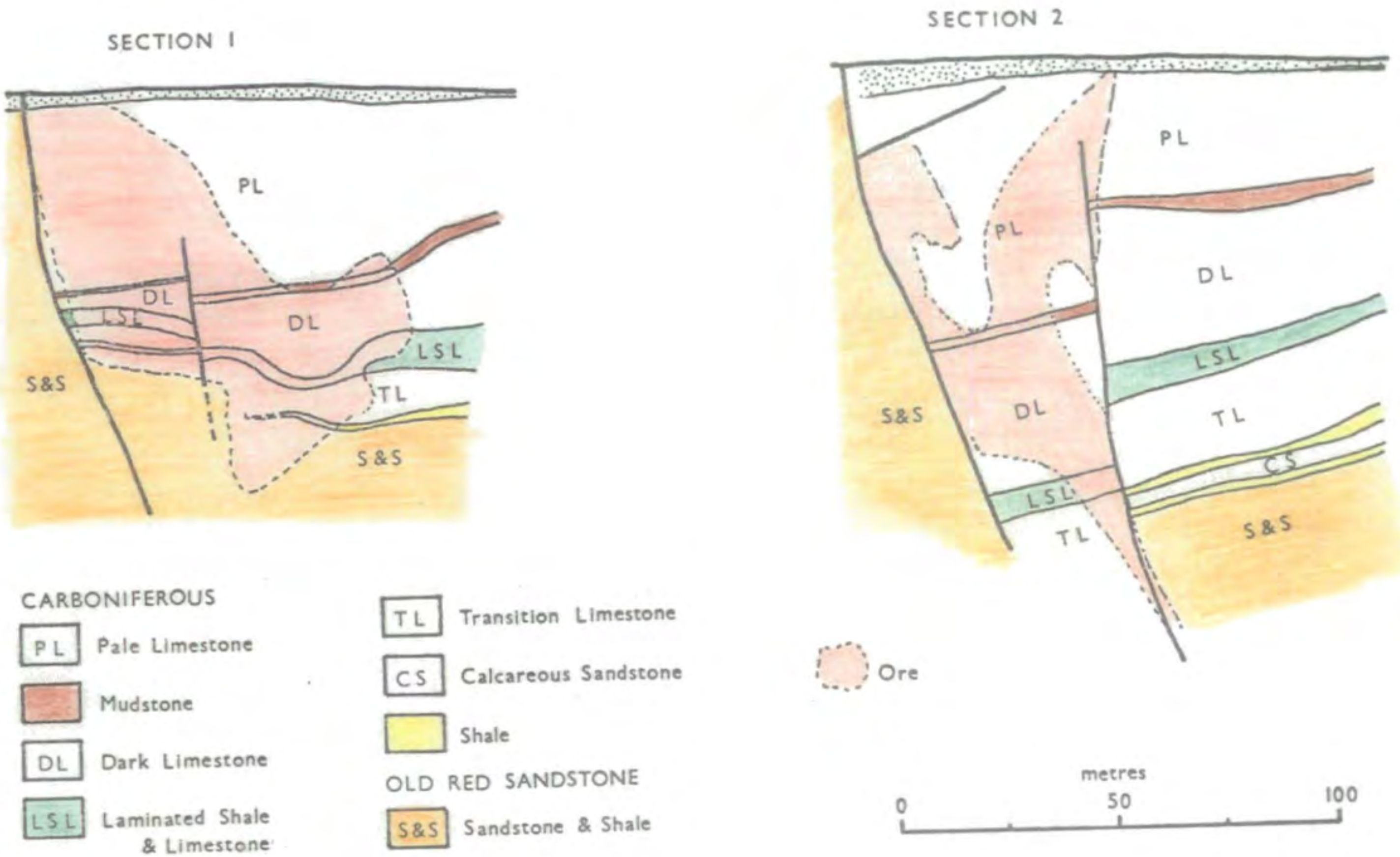

SECTION 1
PL
DL
LSL
DL
LSL
TL
S&S
S&S
SECTION 2
PL
PL
DL
LSL
TL
CS
DL
S&S
LSL
TL
S&S
CARBONIFEROUS
PL Pale Limestone
Mudstone
DL Dark Limestone
LSL Laminated Shale & Limestone
TL Transition Limestone
CS Calcareous Sandstone
Shale
OLD RED SANDSTONE
S&S Sandstone & Shale
Ore
metres
0
50
100

Figure 5 - 3

Cross sections looking west across ore body prior to mining.
Section lines are shown in Figure 5 - 2. Copied from Thompson (1967).

chalcocite, tennantite (mercurian), chalcopyrite and tetrahedrite with the silver mainly in the tetrahedrite. Pyrite, arsenopyrite and galena are rare. The high grade sections carry more bornite, whereas the very low grade margins consist of chalcopyrite. The average sulphide grade is about 3% and the deposit will produce 60,000 tonnes of copper and 100 tonnes of silver. The presence of mercury was discovered by GM Steed of Imperial College. The stability of the mercury and silver minerals indicate temperatures of deposition below 200°C (Morrissey and coworkers 1971).

The main fault is normal in character, trends eastnortheast and dips about 70° north. Several faults, both normal and reverse in type, are present to the north. The eastern, and richest ore zone, occurs in Carboniferous rocks between the two main faults. Altered feldspar porphyry dykes have been intersected in some drill holes. Thompson (1967) believes that there is a genetic relationship between the dykes and the ore. He concludes "although syngenetic causes cannot be exempted, the field relationships favour an epigenetic origin".

Derry (1968) also believes that there is a relationship between the origin of the deposit and the volcanic events of the Viséan. He further suggests that consideration be given to a possible redistribution of copper values from a higher stratigraphic horizon now removed by erosion. Morrissey and coworkers (1971) declare that "in all cases where there is textural evidence .... the dykes were emplaced before the onset of ore mineralization".

One other possibility is that copper from Devonian Sandstones was 'collected' by the Carboniferous calcareous rocks which are juxtaposed to these sandstones by the Gortdrum Fault.

Sampling and Analysis of Gortdrum Host Rocks

Unmineralized core samples collected from the margins of the deposit were analysed for the following elements: lead, zinc, copper, nickel, barium, strontium, rubidium, manganese, iron, arsenic and mercury.

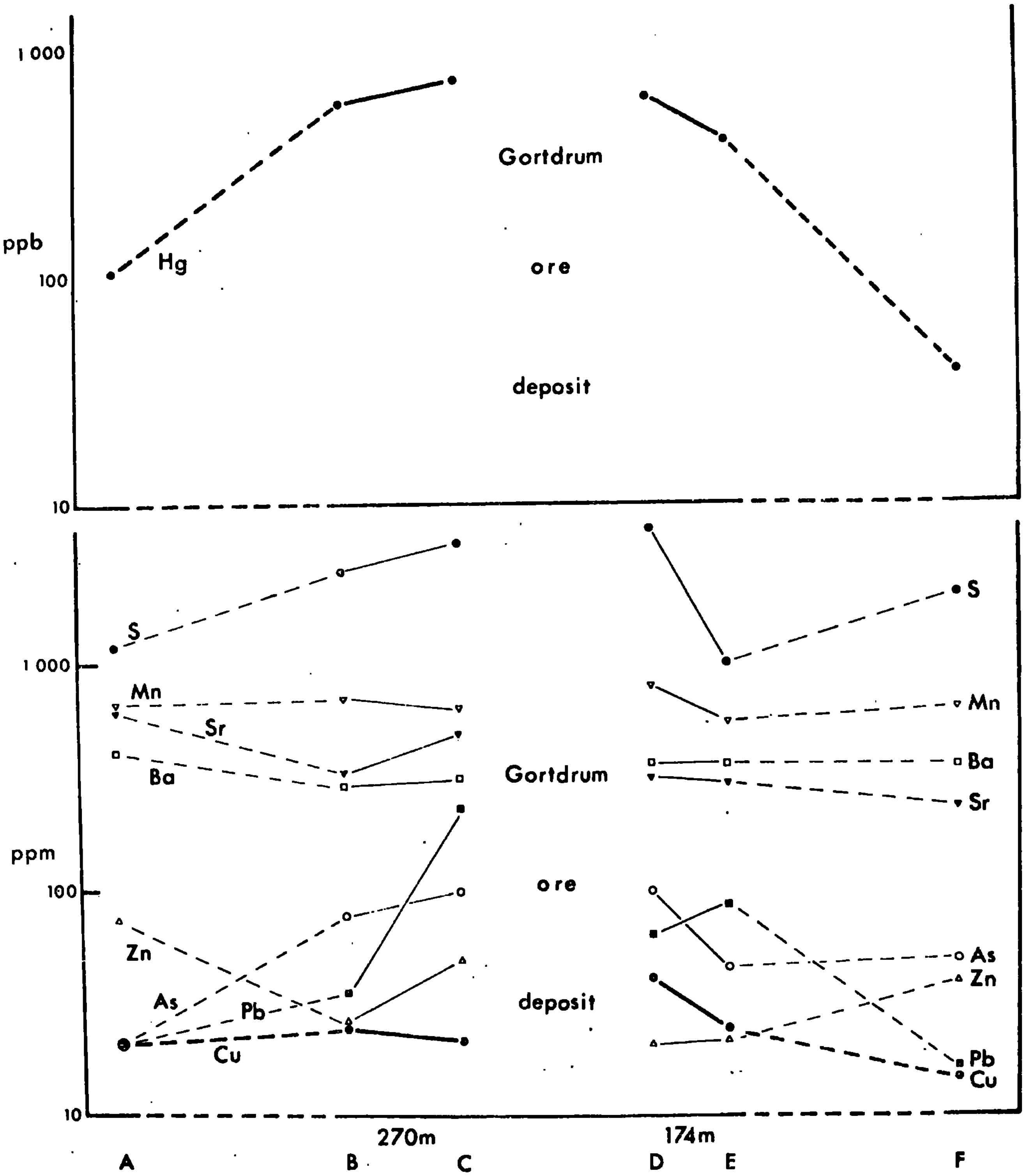

1 000
ppb
100
10
Hg
Gortdrum
ore
deposit
1 000
ppm
100
10
S
Mn
Sr
Ba
Zn
As
Pb
Cu
Gortdrum
ore
deposit
S
Mn
Ba
Sr
As
Zn
Pb
Cu
270m
174m
A
B
C
D
E
F

Figure 5 - 4

Trace element distribution pattern in Limestone and Limestone Shale host rocks to the Gortdrum ore deposit. A and F represent analyses of equivalent rocks at Pallaskenry and Hook Head respectively. B represents averages of trace element analyses in samples from drill holes B 21, B 22, B 24 and B 25. C represents drill holes G 133, G 143 and G 145. D represents drill hole B 30 and E drill hole B 31. Sulphur results are semi-quantitative.

Cores from the Old Red Sandstone surrounding the deposit were also analysed for lead, zinc, copper, nickel and mercury in order to delineate any upthrow mineralization similar to that which aided the discovery of the Tynagh deposit.

In part of the area to the north of the deposit most of the Z zone rocks are faulted out. No results are obtainable for part of the succession in this particular area but the results from several drill holes have been averaged for the sake of graphical presentation. Four samples of the intrusives (991-994) were also analysed.

Gortdrum Results (Appendix 3)

To facilitate comparison the rock types are divided into four groups:

1 Limestones and Limestone Shales
2 Calcareous Sandstone
3 Old Red Sandstone
4 Intrusives

The trace element concentrations of the Limestone and Limestone Shale wall rocks are presented in Appendix 3 and graphically in Figure 5 - 4, along with background comparisons from Hook Head and Pallaskenry. Copper is generally low but lead and arsenic are enriched in the host rocks at Gortdrum. Sulphur is enriched close to the deposit whereas barium, strontium and manganese distributions are unchanged. Despite the possibility of some mercury escape from the background samples, this element is probably relatively enriched at least up to 500 m from the deposit. Zinc may be slightly depleted but it is impossible to prove this statistically from the number of samples analysed.

Samples of Calcareous Sandstone (group 2) collected from cores from the wall rocks at Gortdrum are generally low in lead and zinc. Copper, mercury and barium are close to background excepting a very few anomalies which are not necessarily adjacent to the ore deposit.

Samples of the Old Red Sandstone (group 3) intersected in drill holes, are occasionally high in copper, mercury and barium in the upthrown zone just to the south of the deposit but elsewhere are rarely anomalous.

The Intrusives are relatively high in calcium carbonate, magnesium carbonate, titanium oxide, copper and nickel.

Petrography of Gortdrum Wall Rock

Nine polished sections of the Gortdrum wall rock were studied and compared to polished sections of the same member at Pallaskenry. Pyrite framboids are abundant at Pallaskenry as described in Chapter IV. In three samples (856, 858, 873) collected from drill holes B30, G145 and B24 at Gortdrum, framboids are completely absent. Instead, these samples contain anhedral grains of pyrite approximately 50μ to 75μ across, with lesser amounts of about 7μ grain size. The other six Gortdrum samples (841, 839, 852, 847, 872, 865) from drillholes B30, B31, B25, B24, B22 and B21 contain varying numbers of framboids of 6μ to 12μ in diameter, the individual pyrite crystals in many having coagulated to form uneven pyrite spheres. Remnants of framboidal pyrite are ubiquitous in these six samples as are anhedral grains of pyrite measuring from 6μ to 75μ. Occasional larger anhedral pyrite cubes also occur. Thin sections of the four intrusive samples revealed extensive replacement by calcite.

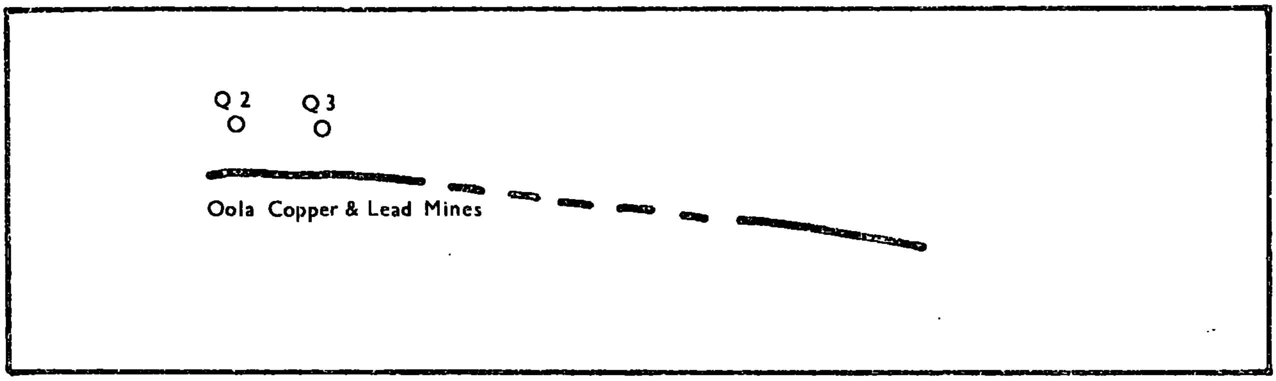
Discussion of Gortdrum Results

The trace element evidence supports Thompson's (1967) contention that the Gortdrum deposit is not syngenetic. The case against a theory of reconcentration of a disseminated copper deposit by lateral secretion from a source bed is harder to prove, the defence being that background content in the contiguous rocks is to be expected, the excess having migrated to the site of the present deposit. The enrichment of lead and arsenic peripheral to the copper deposit is reminiscent of Ballyvergin, and this zoning supports an epigenetic hypothesis. The discovery of mercury at Gortdrum does not, in itself, invalidate a syngenetic-lateral secretion hypothesis for the copper mineralization. Mercury can be deposited from an ore bearing fluid by a drop in temperature and also by neutralization of alkaline waters (White 1967b). It could also have been subsequently trapped by syngenetic copper iron sulphides. It is unlikely that the mercuric ions would precipitate on the sea floor as they are easily transformed into the water soluble methyl and dimethyl mercury by bacterial action within bottom sludges (Jernelöv in Jonasson 1970). It is the unaltered framboids in the host rock a short distance from the deposit that argue most strongly against a lateral secretion factor and hence for an epigenetic theory of formation for this deposit.

The fact that there are anomalous, although variable, concentrations of mercury in the solid rock close to the deposit may be useful in drilling for other mercury-copper deposits. The apparent conversion of the texture of pyrite from framboidal to granular also may be useful in prospecting.

Thompson (1967) has noted that the sulphides at the lower grade margins of the deposit lie parallel to the bedding. This may be due to the mineralizing fluids permeating the shaly limestones and reacting with the local sulphur. Further work on the margins of the deposit is required to ascertain whether the sedimentary-diagenetic iron sulphide has been replaced by chalcopyrite in this region, as for example, at White Pine, Michigan (see Brown 1971).

Anomalous concentrations of copper, mercury and barium in sandstones on the upthrow side of the deposit may represent a root zone if mineralization preceded major fault movements. However, the outcropping rock near the deposit was not analysed and therefore no conclusions regarding field lithogeochemical exploration can be drawn from these results.


Q 2
Q 3
Oola Copper & Lead Mines

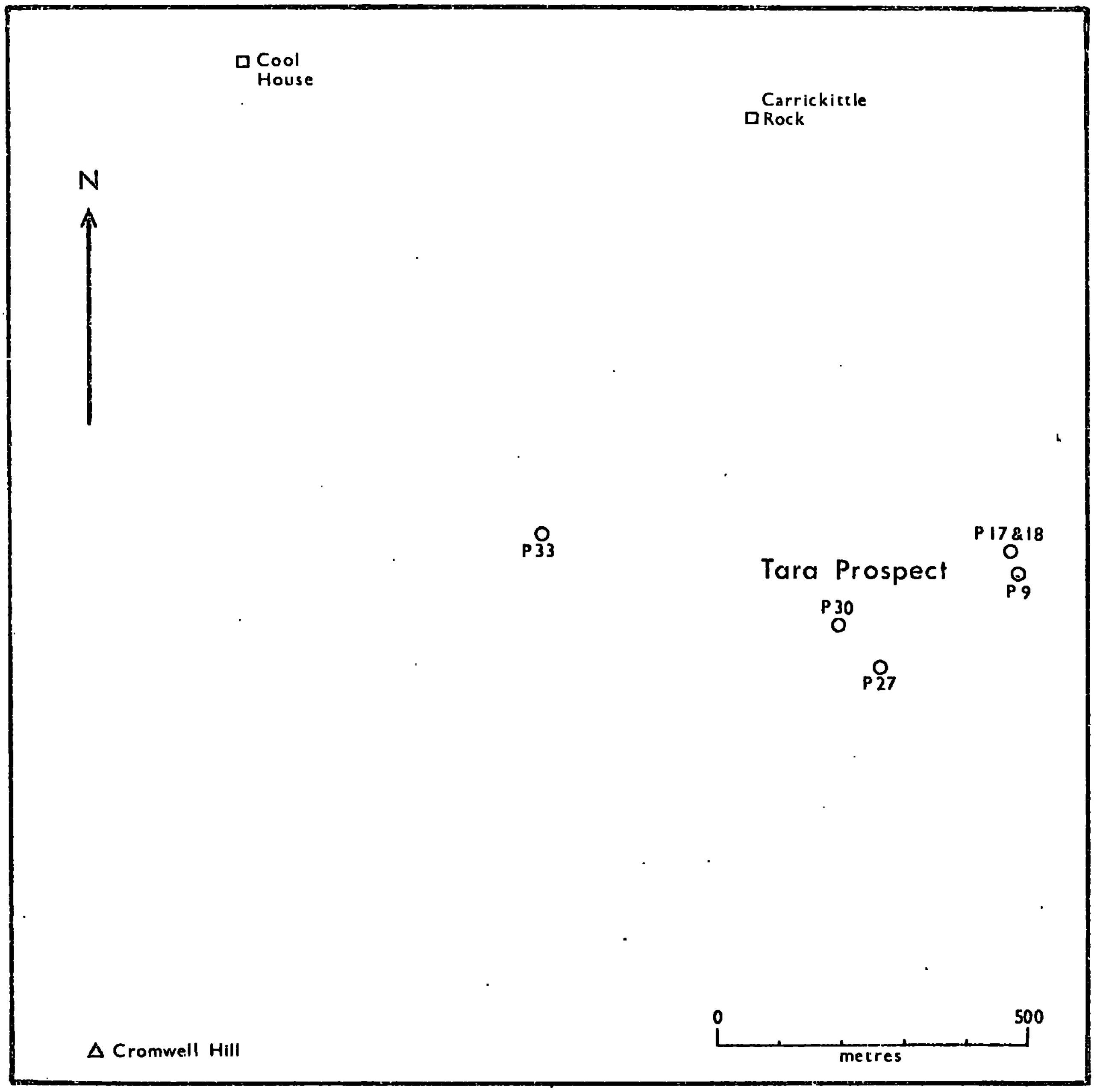

Cool House
Carrickittle Rock
N
P 33
P 17&18
Tara Prospect
P 9
P 30
P 27
Cromwell Hill
0
500
metres

Figure 5 - 5

Top diagram shows the sites of the two drill holes sampled near the defunct Oola Mines.

Bottom diagram shows the sample sites at the Carrickittle prospect near Kilteely.

Both diagrams are to the same scale.

Thin sections show the intrusives to have been strongly altered and partially replaced by calcite. Chemically it is not possible to prove that these rocks are the same as those in the sills. If they are the same then the rocks have been leached of their sodium and some of their potassium. The titania content is remarkably high; the possible reasons for this are 1) the intrusive was more basic than the nearby trachyte sills, or 2) the titania content is a secondary enrichment related to the mineralizing fluids. Neither possibility is especially favoured on present evidence.

The anomalous concentrations of copper and nickel in these samples may relate to precipitation from fluids escaping from the main zone of ore deposition along permeable interfaces between the intrusive and the argillaceous limestones.

The only assertion that can be made from this evidence is that fluids leached the intrusive of alkalis and precipitated calcite, dolomite, copper and nickel and possibly some titania. It is probable therefore, that most if not all of the mineralization postdated the intrusion of the igneous rocks.

Mineralization at Oola

The east-west lode is traceable for 1200 m and several shafts were opened into it during the last century (Cole 1922) (Figure 5 - 5). Chalcopyrite and argentiferous galena occurred in a gangue of barytes in vertical veins. The host rocks are the same as those at Gortdrum and they also include some igneous intrusives.

Sampling at Oola

The only available samples of wall rock were from two cores drilled out 70 m north of the western end of the lode (Figure 5 - 5). Although the holes may have intersected an aureole it was recognised that it would not be possible to construct a trace element profile away from the deposit.

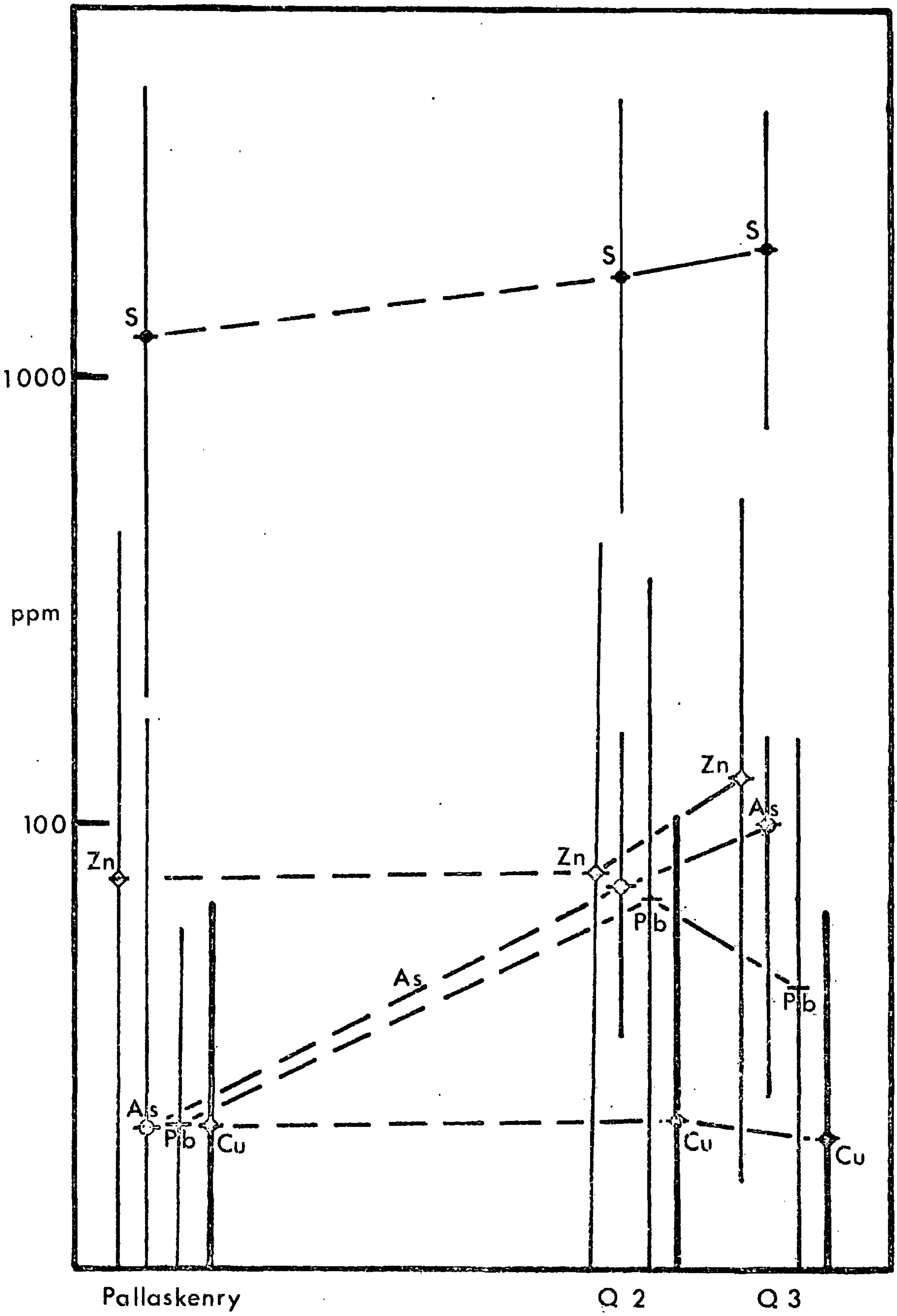

S
S
S
1000
ppm
Zn
Zn
As
100
Zn
Pb
As
Pb
As
Pb
Cu
Cu
Cu
Pallaskenry
Q 2
Q 3

Figure 5 - 6

Trace element distribution and range of values in Limestone and Limestone Shale 70 m north of Oola, with a comparison with the Pallaskenry results. There are too few samples and sample sites to allow an aureole to be defined but arsenic and lead do appear to be enriched and copper is at background level.

Oola Results (Appendix 3)

The analyses of the Limestone Shales and Limestones are presented in Appendix 3 and graphically in Figure 5 - 6 together with a comparison with the Pallaskenry results. Copper is at background level but lead and arsenic are significantly enriched in the wall rocks. Sulphur and zinc may be enriched in rocks intersected by drillhole Q3.

The calcareous sandstone is low in zinc content but occasionally high in lead, copper and barium. The major element chemistry of the intrusives is similar to that found at Gortdrum. The trace element contents, however, are not anomalous.

Petrography of Oola Wall Rock

Several polished sections of the Oola wall rock were studied. Pyrite framboids were abundant in all sections examined. A thin section of the greenish coloured intrusive (493) showed extensive replacement by calcite.

Discussion of Oola Results

Again there is no anomalous concentration of copper in the wall rocks at this distance from the lode but lead and arsenic are enriched in a manner reminiscent of the Ballyvergin and Gortdrum deposits. The fact that, in contrast to Gortdrum, pyrite framboids are abundant at Oola implies that no similar deposit is present in the vicinity of this lode at this point.

The Oola lode then is epigenetic and the presence of galena and barytes suggests that it is further removed from the source of the mineralizing solutions as compared to Gortdrum. Again, at least most of the mineralizing fluids were circulating after the emplacement of the intrusive rocks. The presence of about 2% titania in the intrusives suggests a comparison with Gortdrum.

Mineralization at Carrickittle (near Kilteely)

Nothing has been published on this deposit to date. The information here is based on drill hole records provided by Brian Byrnes with the permission of MV O'Brien. The deposit consists of galena, sphalerite and pyrite pods and flats in certain horizons near the base of the Waulsortian mudbank complex and also (in one drill hole) in the intrusive trachyte. The sulphides are fine grained and the sphalerite is honey coloured. The host rock is occasionally dolomitized and calcite occurs as a gangue mineral. A large number of cavities were encountered during the drilling. The deposit is rather similar to that at Tynagh but without the latter's minerological complexity and size.

The uneven distribution of the ore, such as its non occurrence in some of the central drill holes and its emplacement in the intrusive, argues for a replacement theory of deposition.

Sampling at Carrickittle

Six drill cores were sampled: 9, 17, 18, 27, 30 and 33 (Figure 5 - 5), and from these 56 samples were collected. Drill holes 9, 17 and 18 intersected sulphide mineralization at or near the bottom of the Waulsortian mud bank complex. Waulsortian limestone from Cool House and Carrickittle Rock was also sampled (Figure 5 - 5).

Carrickittle Results (Appendix 3)

The samples from Cool House and Carrickittle Rock contain no anomalous concentrations of trace elements. In the drill cores anomalous concentrations of zinc are common especially in the vuggy portions of the Waulsortian limestone. Manganese is also strongly enriched especially outside of the main zone of mineralization. Lead is often high but copper more rarely so. Strontium is depleted in holes 27 and 30 (the former probably because of dolomitization), as well as in rocks adjacent to the mineralized zones. Iron is relatively high in samples from drill hole 27 where strontium is low implying that the dolomite is ferroan. Mercury is enriched in only one of the samples analysed. The mineralization is too sporadic and the drill holes too sparse to allow a graphical presentation of the results.

The intrusive rocks sampled are low in sodium and high in potassium. One of the samples is enriched in carbonates but both contain an unremarkable amount of titania, the level being comparable to that of the trachytes in the nearby sills.

Discussion of Carrickittle Results

The precipitation of the sulphides was clearly epigenetic and the main problem is the source of the mineralization. It is tempting to assume that the metals were derived from the same source as that which supplied the Gortdrum mineralization, the Tara Prospect near Carrickittle being the outer zinc-lead zone in such a model. Equally, it may be postulated that the metals were derived from Lower Carboniferous rocks in the Limerick Basin and migrated up dip to Carrickittle in the manner suggested by Noble (1963) and Dozy (1970) for the Mississippi deposits. In mode of occurrence it is certainly similar to the Mississippi type of mineralization. The sulphides have been precipitated in patches that may have been small caverns and many voids, presumably never filled, have been intercepted by drilling. Even today the Lower Limestone Shales are about a kilometre deep in the centre of the basin; with heat from the intrusions, however, it is possible that formation waters carrying lead and zinc deposited their metals on mixing with waters containing hydrogen sulphide and sulphur in the Waulsortian mud bank complex.

From the results it is clear that the intrusive has been leached of its sodium but is quite high in potassium. This rock contains only a quarter of the titania found at Gortdrum and Oola, the content being similar to that in the adjacent sills. The replacement of the intrusive by calcite and dolomite is much more restricted here compared to the other two mining areas.

There is no suggestion of copper enrichment at depth.

It is not possible to decide between the two hypothese outlined above regarding the source of the metals from present data. However, it may be that the mineralizing fluids travelled some distance before precipitating their metals in the bank limestones.

Summary and Conclusions

The trace element evidence, in conjunction with polished section work, supports an epigenetic theory for the deposition of the Gortdrum copper-silver-mercury deposit. The origin of the sulphur presents a problem. Greig and coworkers (1971) obtained a δS^{34} value in barytes of +17.5 per mille. As this result lies within the field of δS^{34} values for Lower Carboniferous evaporites, Solomon and co-workers (1971) suggested that connate waters within the Lower Carboniferous rocks contributed the sulphate of the barytes. The δS^{34} values in the sulphides range from -7 to -22 per mille (Greig and co-workers 1971). This broad spread of negative values could be explained as being the result of biogenic reduction of the sulphate rich waters to give hydrogen sulphide. Fluids containing hydrogen sulphide may have been present throughout this area in all the Tournaisian rocks. If so, this would imply that the mineralizing fluids rose up along the Gortdrum Fault, the metals being precipitated as sulphides on mixing with the hydrogen sulphide bearing fluids. The Oola vein minerals were probably derived from the same source. One interesting phenomenon is the occurrence of relatively high titania content in the intrusives, compared to the outcropping sills nearby and the country rocks. In contrast titania is not anomalous in the intrusives at the Tara Prospect near Carrickittle. There is no evidence implying similar origins for the mineralization near Carrickittle and it could be that this typical though small Mississippi type lead-zinc deposit was derived from formation waters expelled from the Limerick Basin (cf Noble 1963).

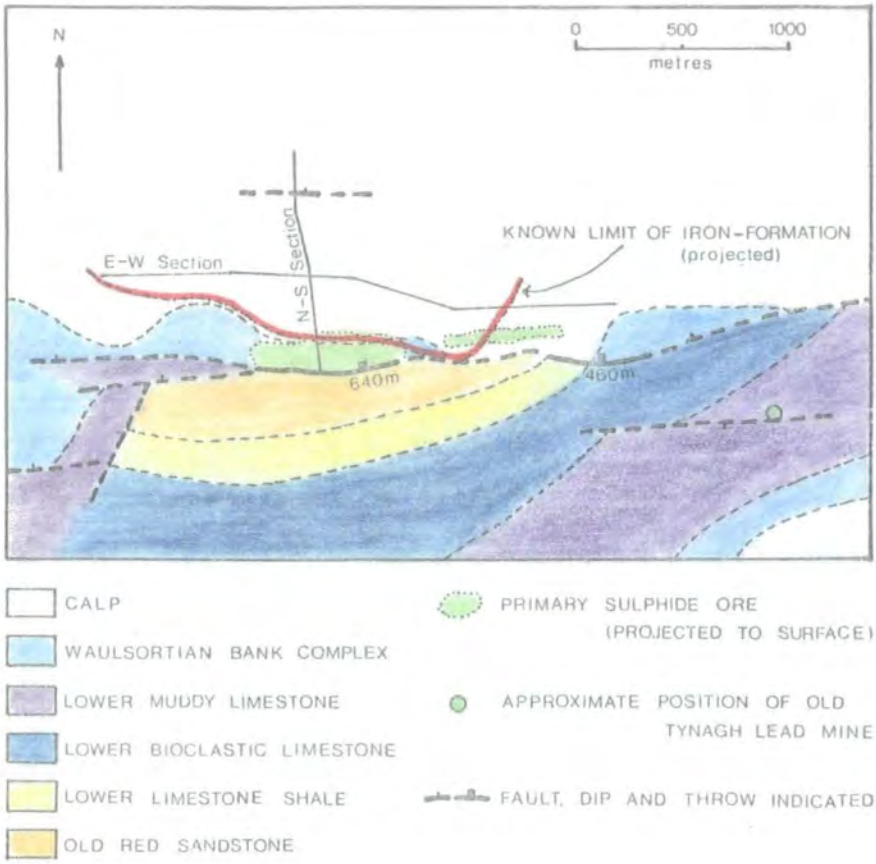
VI THE TYNAGH IRON AND BASE-METAL DEPOSITS

Mineralization

The primary ore at Tynagh consists of fine grained pyrite, galena and sphalerite together with some chalcopyrite and tenantite. These sulphides are often intimately mixed with barytes. The ore replaces and infills the Waulsortian mud bank complex, and to a lesser extent, the Lower Limestone. The host rocks in parts of the orebody had previously been altered to a ferroan dolomite (Schultz 1966b).

Overlying this deposit is a secondary ore consisting of an unconsolidated residuum of the primary deposit and host limestone. This residual orebody is composed of a dark mud containing fragments of primary mineralization ranging in size from microscopic particles to boulders of 2 m in diameter (Morrissey and Whitehead 1969). About 60% of the residuum has been classified as sulphide ore. The Tynagh residual orebody is similar to one occurring in Viséan (Windsor) limestone at Smithfield, Nova Scotia. The Smithfield deposit consists of angular blocks of sulphides and of grey limestone in a muddy matrix of finely broken ore and limestone (Weeks 1963). The entire Tynagh ore deposit contains 600,000 tonnes of lead, 500,000 tonnes of zinc, 50,000 tonnes of copper, 600 tonnes of silver and 2,000,000 tonnes of barytes.

The ore zone lies adjacent to an east-west fault, with a dip slip of at least 640 m, which brings Old Red Sandstone against the deposit (Schultz 1966a). A bedded iron-formation, associated with tuffs, lies to the north of the sulphide deposit at about the same stratigraphic horizon (Figures 6 - 1 and 6 - 2). Derry, Clark and Gillatt (1965) erected an attractive hypothesis to explain the juxtaposition of both metaliferous deposits. They postulated that mineralizing solutions rose along the east-west fault and seeped into an area of recent organic growth of the mud bank complex. Here, lead, zinc, copper, silver and some iron were deposited as sulphides and barium as the sulphate.


N
0
500
1000
metres
KNOWN LIMIT OF IRON-FORMATION
(projected)
E-W Section
N-S Section
640m
460m
CALP
WAULSORTIAN BANK COMPLEX
LOWER MUDDY LIMESTONE
LOWER BIOCLASTIC LIMESTONE
LOWER LIMESTONE SHALE
OLD RED SANDSTONE
PRIMARY SULPHIDE ORE
(PROJECTED TO SURFACE)
APPROXIMATE POSITION OF OLD
TYNAGH LEAD MINE
FAULT, DIP AND THROW INDICATED

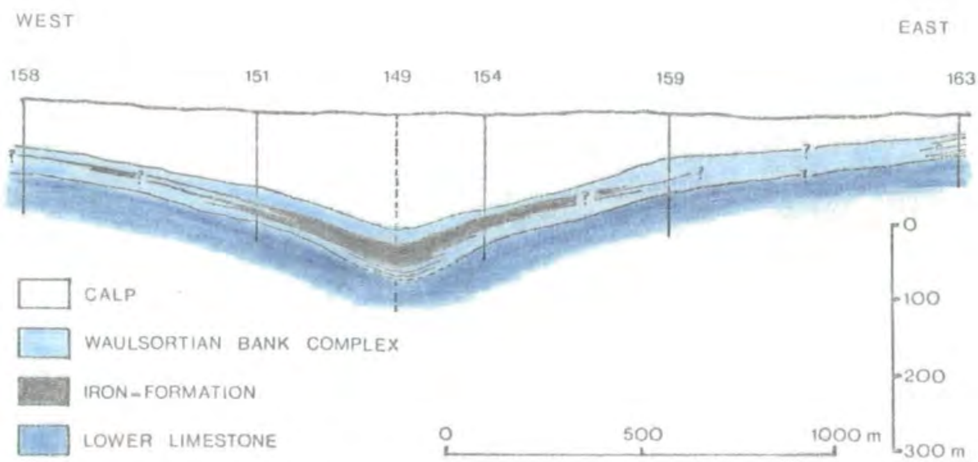

WEST
EAST
158
151
149
154
159
163
0
100
200
300 m
CALP
WAULSORTIAN BANK COMPLEX
IRON-FORMATION
LOWER LIMESTONE
0
500
1000 m

Figure 6 - 1

Top diagram is a geological map of the Tynagh Mine area copied from Morrissey and Whitehead (1969).

Bottom diagram is an east-west section along a drill hole section figured in top diagram, copied from Schultz (1966a). The iron-formation appears to thicken at the deepest part of this section at a point which lies northnorthwest of the maximum throw of the North Tynagh Fault.

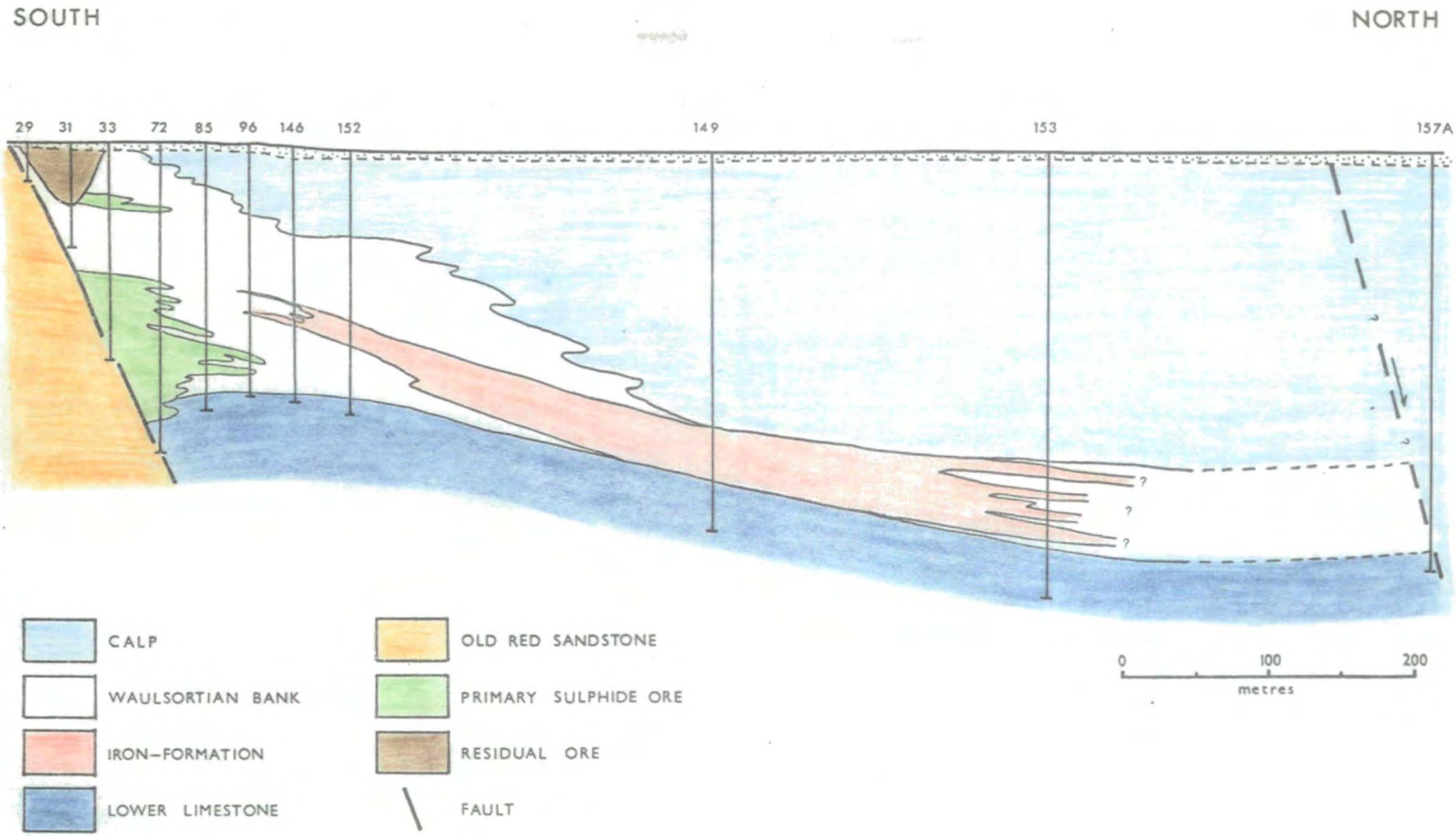

SOUTH
NORTH
29
31
33
72
85
96
146
152
149
153
157A
CALP
WAULSORTIAN BANK
IRON-FORMATION
LOWER LIMESTONE
OLD RED SANDSTONE
PRIMARY SULPHIDE ORE
RESIDUAL ORE
FAULT
0
100
200
metres

Figure 6 - 2

North-south section along a drill hole section shown in Figure 6 - 1. Copied from map kindly supplied by RW Schultz.

The silica, manganese and much of the iron, however, remained in solution and were deposited in a protected basin off the reef. Green tuff bands interbedded with iron ore point to simultaneous local volcanic activity. An assumed thinning of some of the Carboniferous formations towards the fault led Derry and coworkers (ibid) to conclude that movement continued throughout ore deposition.

Schultz (1966b) disagreed with this hypothesis, postulating instead that this iron deposit was derived by intensive chemical weathering of lower Dinantian sediments which had been exposed on newly emergent land. The sulphide-barytes mineralization was genetically independent of the iron-formation, according to Schultz (ibid), and post dated the Stephanian. As evidence he emphasized that the sulphides had been deposited in post lithification fractures and that part of the sulphide body occupied rocks younger than the iron deposit. He proposed an epigenetic-hydrothermal model for the origin of the sulphide-barytes deposit.

Aims

The disagreement noted above is highly significant regarding the age of mineralization and I decided to carry out some geochemical investigations in order to see if either theory could be supported or rejected.

Methodology

The belief that the iron-formation is a sediment is not in dispute. If this sediment were found to contain percentages of elements found in the sulphide-barytes deposit then we might take this as support for the suggestion that the iron deposit was precipitated from escaped mineralizing solutions. On the other hand, if no such concentrations were found this would not invalidate this 'exhalative' hypothesis because 1) these elements may not have been present in the solutions at that time, 2) if present, they may have been precipitated epigenetically or 3) if present, and liberated into the sea, they may not have been precipitated in the oxidizing environment then obtaining.

A second method is to analyse the rock for major elements and then on this basis assign it to a category previously erected by workers on other iron deposits. This is inferior methodologically because the examples in the category may have been chosen for their 'proving' power.

Another approach to the whole problem is to carry out trace element analyses on samples of host rocks both close to and at a distance from the sulphide-baryte deposit in order to find evidence supporting escape of ore elements into the surrounding sea.

All these methods of approach were used in this study.

Trace Element Results of the Ironstones (Appendix 3)

There are few anomalous concentrations of trace elements in the nine samples analysed. The exceptions such as the 2400 ppm lead and nearly 1% barium in sample 655 correlate with high values for manganese which is well known as a scavenger. The high zinc in samples 671 and 680 may be epigenetic as they were collected from core drilled from close to the primary sulphide-baryte deposit. Added to this, no visual sulphide-baryte lenses have been recorded by Schultz (1966a).

Major Element Results of the Iron-formation

The results along with the analysis quoted by Schultz (1966a) are presented in Appendix 3. They are in accord with the Schultz analysis being low in alumina and phosphate and consisting mainly of iron oxides and silica. Three samples taken from a manganese rich horizon about 1.5 m thick from the northern most drill hole contain 33%, 78% and 79% Mn_2O_3.

Discussion of Iron-formation Results

Relying on its chemistry Schultz (1966a) classifies the Tynagh iron deposit as an oxide-facies iron-formation of Lake Superior type.

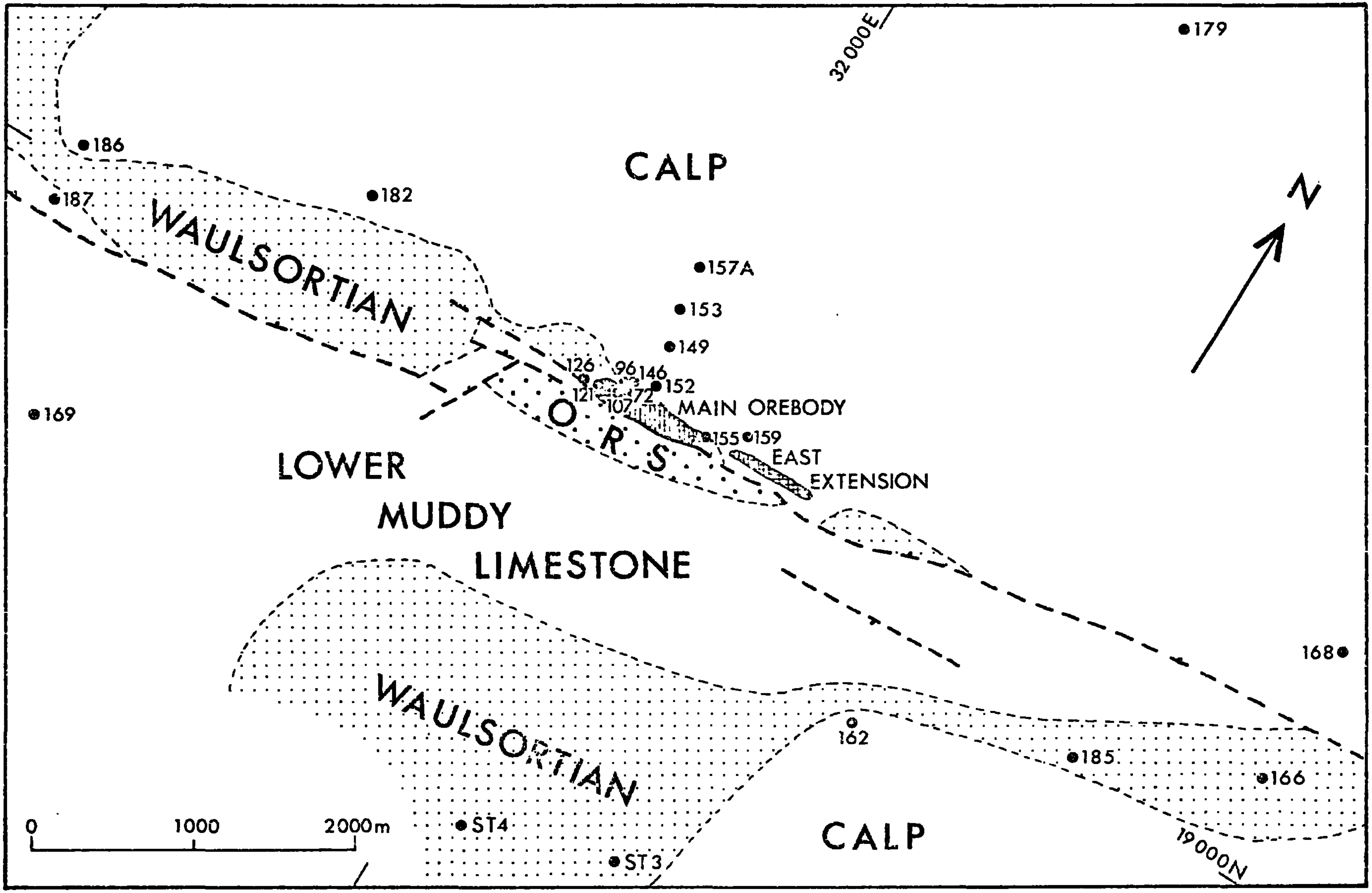
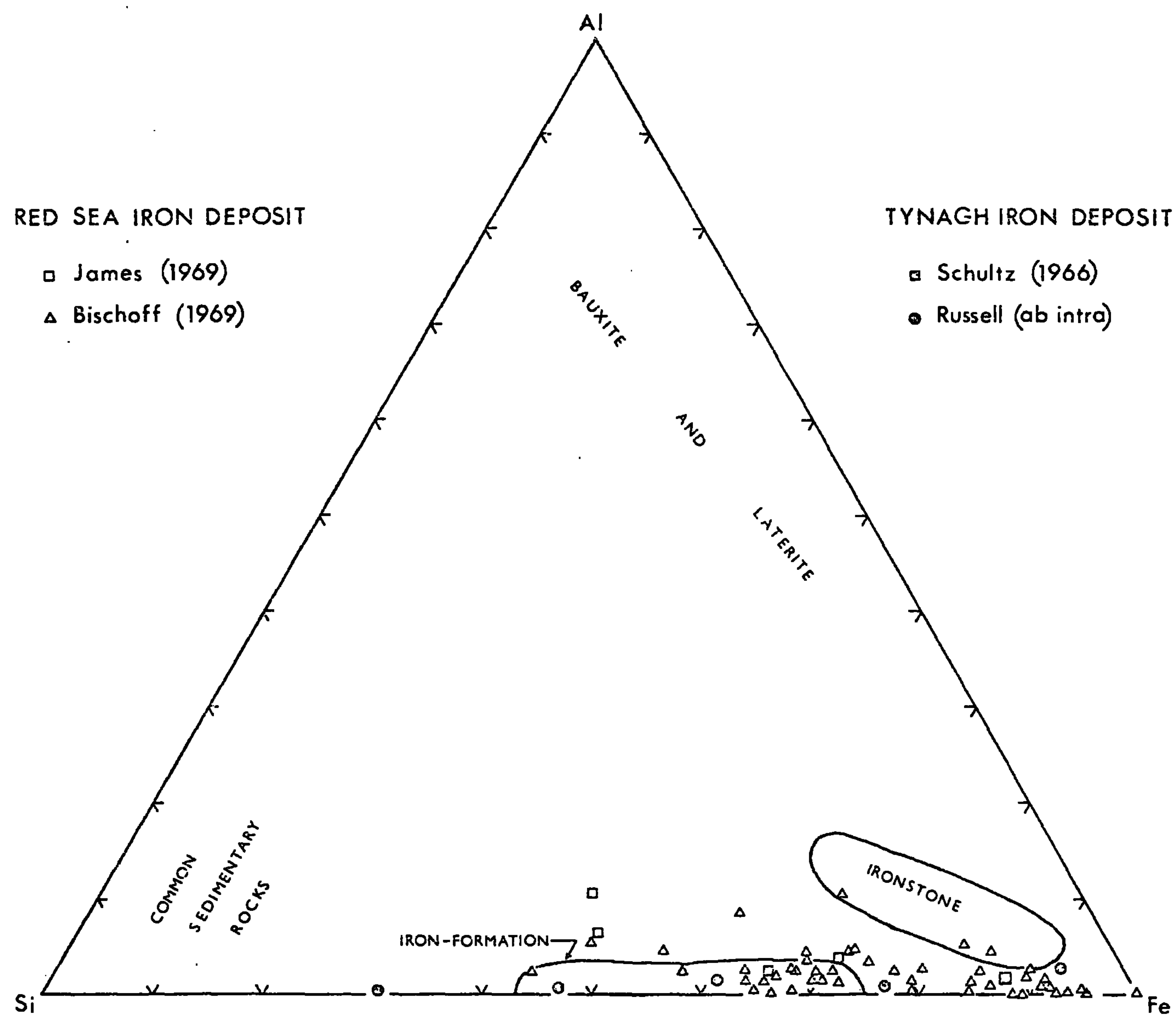

N
32 000E
179
186
187
182
CALP
WAULSORTIAN
157A
153
149
126
96
146
152
121
107
72
MAIN OREBODY
155
159
EAST
EXTENSION
O. R. S.
169
LOWER
MUDDY
LIMESTONE
168
WAULSORTIAN
162
185
166
0
1000
2000m
ST4
ST3
CALP
19000N

Figure 6 - 3

Plan of the Tynagh Mine area showing the drill holes sampled. The sulphide ore bodies are projected to the surface. From mine plans kindly supplied by RW Schultz. Geological boundaries copied from Morrissey and Whitehead 1969.



Al
Si
Fe
RED SEA IRON DEPOSIT
James (1969)
Bischoff (1969)
TYNAGH IRON DEPOSIT
Schultz (1966)
Russell (ab intra)
BAUXITE AND LATERITE
COMMON SEDIMENTARY ROCKS
IRONSTONE
IRON-FORMATION

Figure 6 - 4

ASF diagram showing compositional fields of typical ironstone and iron-formation (from James 1969) compared with Red Sea sediments and the Tynagh iron-formation. Al+Si+Fe=100 weight percent.

He supports James's (1954) hypothesis for the origin of the Precambrian iron-formations; that is, iron and silica were derived by deep chemical weathering of a low lying land mass and deposited in a bordering marine basin. Mechanical erosion was relatively insignificant. Figure 6 - 4 shows the division of sedimentary iron deposits into ironstones and iron-formation on the basis that Al+Si+Fe=100 weight per cent (James 1969). In this diagram the assignment of the Tynagh deposit to iron-formation seems reasonable. The recent discovery of the Red Sea iron rich 'exhalative' sedimentary deposits however raises other possibilities. James (ibid) points out that the Red Sea iron deposits display characteristics of both the typical iron-formation (many of the samples have similar silica and iron contents as well as titania and phosphate) and ironstones (some samples have high alumina contents) (Figure 6 - 4).

The sediment outside of the Red Sea hot brine basins consists of calcareous shells, detrital quartz, feldspar and clays (Emery and coworkers 1969) so the high Al content of the iron deposit may be a detrital addition. If so then the Tynagh iron deposit could also be equated with the recent Red Sea iron rich sediments because at Tynagh the enclosing rocks are mainly carbonates and Al_2O_3 contents are very low.

The Red Sea iron sediments with their associated copper, zinc and lead sulphides and amorphous silica were and are precipitating from hot brines discharging into the sea through the Red Sea floor. The presence of the base-metals and the dearth of manganese (except in two samples reported by Bischoff 1969) is due to the relatively low Eh of the system. Both the iron and the manganese content of the brines exceed normal sea water by a factor of 10^4 or 10^5 so most of the manganese has been presumably flushed out of the brine pools (Hartmann 1969).

The Tynagh deposit is even more similar to the cool spring precipitates

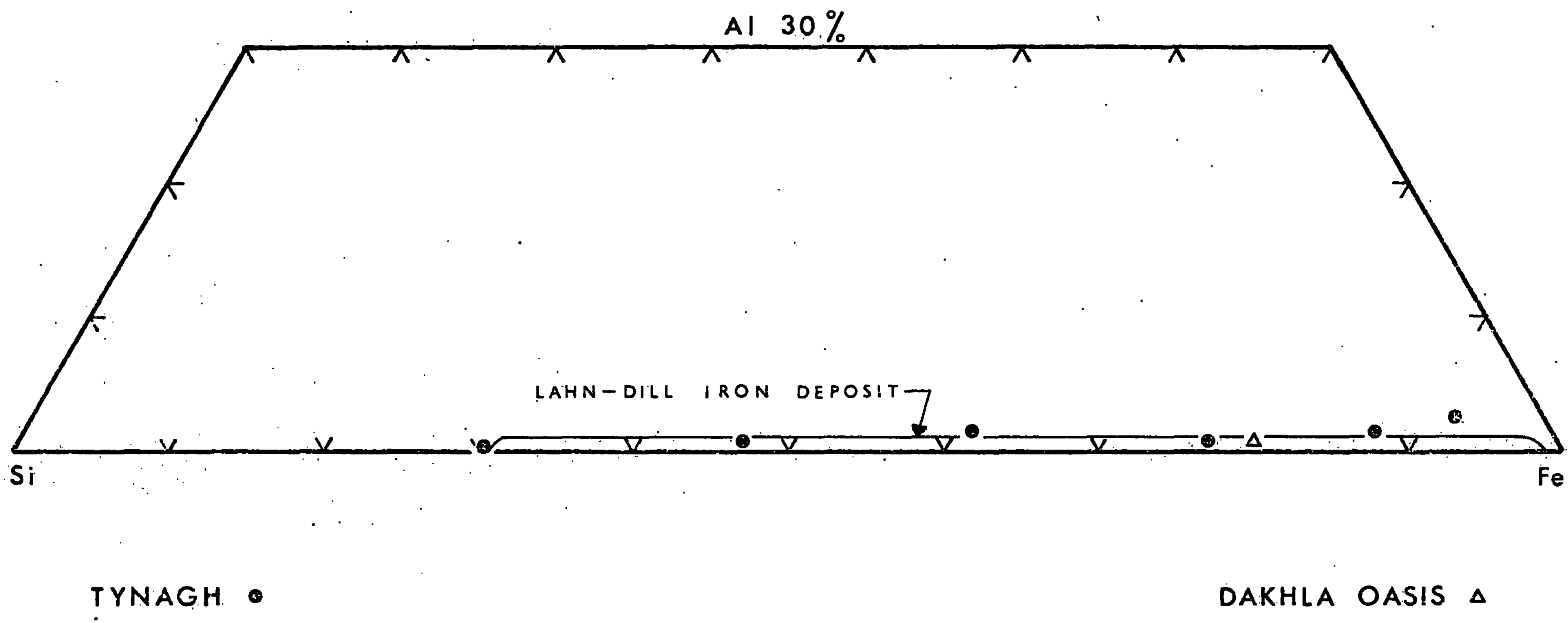

Al 30%
LAHN-DILL IRON DEPOSIT
Si
Fe
TYNAGH
DAKHLA OASIS

Figure 6 - 5

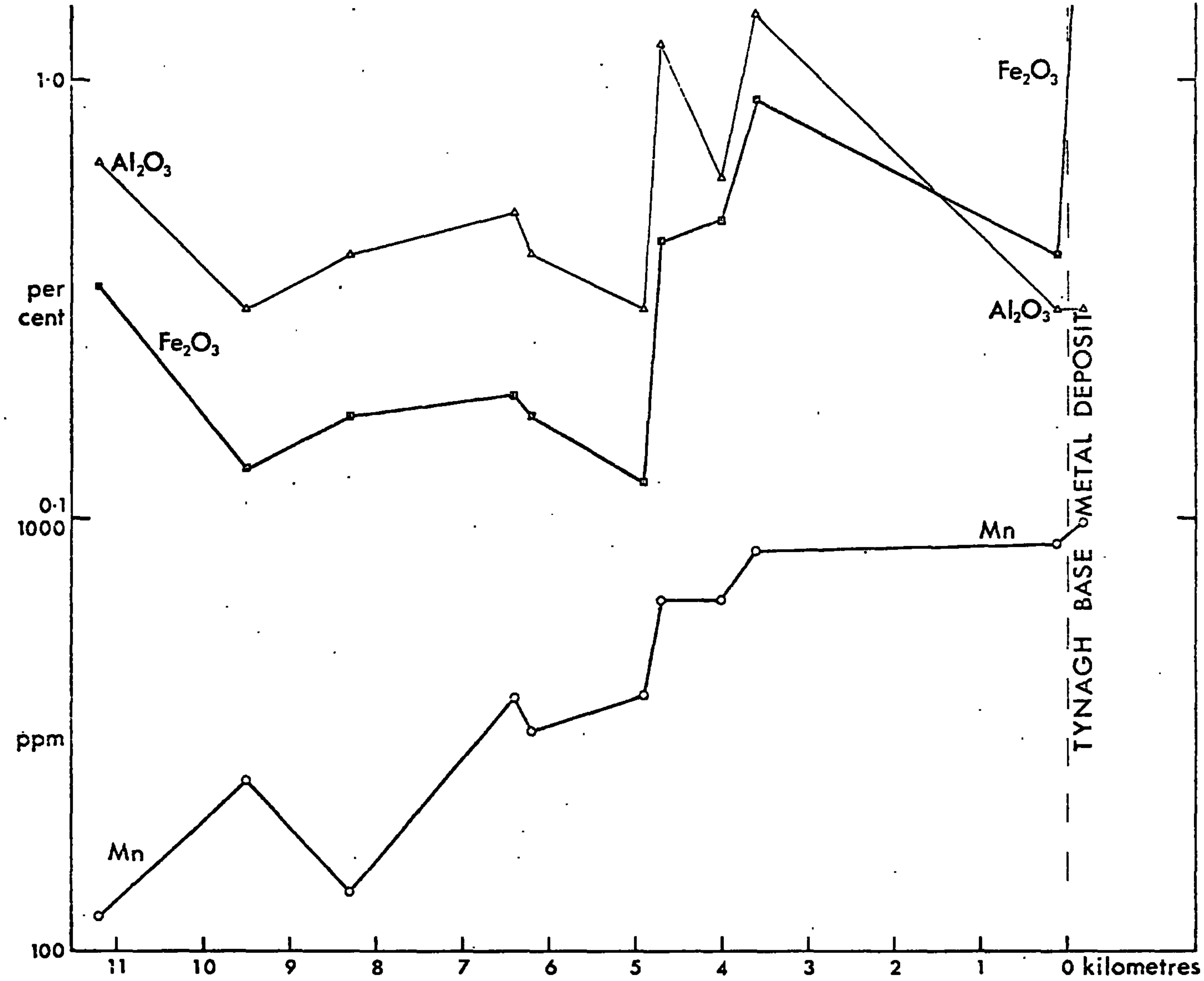
A comparison of the Tynagh iron deposit with the Lahn-Dill iron deposit as analysed by Harder (1954; 1964) and with a precipitate at a spring in the Dakhla Oasis, UAR (Harder 1964). Al_2O_3 is normally present in the Lahn-Dill area in concentrations ranging between 0.1 and 1% and rarely up to 3% (ibid).

in the Dakhla Oasis, Egypt (UAR) as analyzed by Harder (1964) (Figure 6 - 5).

If we restrict our comparisons to the Upper Palaeozoic then we find that the Tynagh deposit stands in strong contrast to the Carboniferous Coal Measure ironstones of the British Isles (Hallimond 1925) which generally plot out in the typical ironstone field. On the other hand they are chemically similar to the Devonian Lahn-Dill sedimentary iron ores (see Harder 1954; 1964) (Figure 6 - 5 and Appendix 3). Although views vary regarding the detailed origin of the deposits (Schneiderhöhn 1944); Oftedahl 1958; Borchert 1960; Rösler 1964; Harder 1964) they are generally considered to be the type example of the submarine - exhalative class of iron ores. In terms of modern theories of ore genesis as influenced by isotope studies (see Craig 1966; Doe and coworkers 1966; White 1968), we would not insist or perhaps necessarily expect the exhalations to be gases, nor need they be magmatic hydrothermal in origin but merely hot waters containing leached iron and silica discharging onto the sea floor.

Lahn-Dill type ores also occur in the Devonian rocks of the Jesenčky Mountains of Czechoslovakia where they frequently lie along strike from but pre-date copper-lead-zinc ores of uncertain origin (Pouba 1971).

An even more arresting comparison is with the Atasu type deposits of Central Kazakhstan. Shcherba (1968) has described the type as consisting of stratabound sedimentary iron, manganese and lead-zinc ores in Upper Devonian rocks. They are often associated with superposed hydrothermal copper-zinc-lead-barite deposits. Both the syngenetic and the epigenetic members are considered to be derived from the same ore bearing solutions. One of the Atasu iron-manganese deposits (Karadzhal) has been described by Maksimov (1960). It is composed of hematite, jasper, magnetite and small quantities of iron



1·0
per
cent
0·1
1000
ppm
100
Al_2O_3
Fe_2O_3
Mn
Fe_2O_3
Al_2O_3
Mn
TYNAGH BASE METAL DEPOSIT
11
10
9
8
7
6
5
4
3
2
1
0 kilometres

Figure 6 - 6

A graphical presentation of the apparent manganese aureole developed to the westnorthwest of the Tynagh sulphide-oxide deposits in the Waulsortian limestones. The iron oxide and alumina content correlate well except close to and in the sulphide deposit. In contrast manganese appears to be broadly independent. The aureole could be due to sedimentary enrichment (in relatively high Eh - pH conditions) of manganese originating near the Tynagh chert - iron oxide deposit. Alternatively, the enrichment may relate to an as yet unknown origin.

The three sample sites in and close to the deposit are drill holes 186, 126 and 107.

chlorite, siderite as well as braunite, hausmanite and jacobsite. The three manganese minerals are restricted to the eastern end of the deposit. There are a few small intercalations of iron rich barytes and a little pyrite, arsenopyrite, chalcopyrite, galena, sphalerite and tetrahedrite.

Sampling of Carboniferous Limestone

Samples were collected from unmineralized core, drilled out during exploration away from the known deposit (Figure 6 - 4). Also twenty two samples of Waulsortian mud bank were collected from exposures 4 km to 11 km west and northwest of Tynagh.

For the purposes of this survey, the Lower Carboniferous succession was divided into three stratigraphical units.

1) Dark Muddy Limestone Calp
2) Waulsortian mud bank in the mine area, and pseudobreccias and muddy limestone to the north
3) Lower Muddy Limestone and Lower Limestone Shale.

It is impossible to draw an accurate time division between units 1 and 2, but pseudobraccias are counted as being approximately equivalent to the mud bank complex, the clasts being composed of that material apparently deposited in an unconsolidated state.

Carboniferous Limestone Trace Element Results (Appendix 3)

Regarding primary trace element contents no consistent enrichment of lead, zinc, copper and barium at any one horizon has been found. The manganese content is erratic, but in contrast is enriched in the Waulsortian and its equivalents as well as in the Calp, relative to that in the Muddy Limestone. Judging from the few Waulsortian samples analysed for manganese there is a suggestion of an extremely extensive sedimentary syngenetic aureole to the Tynagh deposits (Figure 6 - 6). The background found for this metal in the Waulsortian mud bank complex is less than 30 ppm and yet there is a gradual and

and uneven increase from about 120 ppm eleven kilometres west-northwest of Tynagh to 847 ppm close to the deposits. Much more detailed work is required to establish this apparent aureole. Strontium is enriched in the highest Calp sampled. Iron and rubidium are apparently lowest in the Calp and part of the Waulsortian and highest in the Lower Muddy Limestone. Higher values of alumina are found in the Lower Muddy Limestone than in the Calp or in the Waulsortian. The sample sites are too scattered and the trace element values too erratic to allow graphical presentation of the results close to the deposit. Not unexpectedly, several of the cores from near the deposit are enriched in some trace elements (notably manganese, zinc, mercury, lead and arsenic), as are samples from bore hole 187 through the North Tynagh Fault, 3.5 km to the west of the main deposit (Figure 6 - 3).

A few other cores at some distance from known mineralization also contain anomalous contents of trace elements. These cores are 153, 159 and 166.

Interpretation of the Carboniferous Limestone Trace Element Results

There is no support for the syngenetic theory for the base-metal deposit to be found in this data. It is possible that the increase of manganese and strontium up the succession and the spread of the manganese in the Waulsortian are related to 'exhalations' but further work is required to establish this beyond doubt.

A by-product of this investigation was the discovery of anomalous concentrations of trace elements in three of the cores sampled away from the deposit. Insufficient samples have been analysed to say anything definitive on this finding. The anomalies in drill hole 166 could be due to the presence either of ore or of one of the Tynagh Faults but those in drill hole 153 are difficult to explain though they may relate to a local unfound pod of ore. Samples from drill hole 159 contain high concentrations of a number of elements. It may be that this enrichment is related to the newly discovered eastern zone of mineralization at Tynagh (See Figure 6 - 3). More research is necessary to test this possibility but if this proved correct, it would support the idea of subjecting core samples to trace element analysis as a basic part of mineral exploration.

Discussion

The hypothesis linking the iron-formation at Tynagh to the base-metal mineralization (Derry, Clark and Gillatt 1965) is made the more attractive by the discovery of the Red Sea 'syngenetic' deposits. The coincidence of certain chemical parameters found here also support this theory. If this were the case, we should have to assume a model in which iron and manganese were dissolved in hot waters which escaped into the sea near the present Tynagh Fault. The iron would have been precipitated mainly as ferric oxide with the increase of Eh due to dissolved oxygen in the sea water. The manganous ion reaches its limits of solubility in increasing Eh conditions a little later than the ferrous ion (Krauskopf 1957) thus explaining the manganese rich bed in a section of the northern portion of the iron deposit and perhaps the anomalous concentration of manganese in the Waulsortian limestones to the westnorthwest. There was apparently no further escape of iron into the sea after mid-Dinantian times. It may be significant that there was probably a pyrite rich zone at the top of the epigenetic base-metal sulphide deposit (Morrissey and Whitehead 1969) which apparently is later than the iron formation. The more soluble manganese could still have escaped which may explain its greater concentration in the Calp whereas iron is low relative to the older Carboniferous rocks. The strontium in the upper Calp could conceivably owe its enrichment to recrystallization and dolomitization of limestone during mineralization, but the depletion of this metal adjacent to the orebody is not well pronounced.

In contrast there are some theoretical objections to the deep weathering hypothesis for the origin of the iron formation. Krauskopf (1956) points out that silica in most stream water is in solution mostly as the essentially unionized monosilicic acid and does not therefore coagulate on contact with sea water. In fact sea water actually causes dilute sols to disappear (Bruevich 1953 quoted by Krauskopf 1956). Also the conditions on a low lying land mass in Lower Carboniferous times would have been entirely different to those obtaining in the Precambrian. A 'coal' forest would have grown in mid-Dinantian times as in northern England (Eastwood 1935) and any iron would have been trapped in fresh water swamps as siderite (Berner 1970; James 1966) and even when finally oxidised would have formed ferric oxide.

Schultz (1966a) assumes base-level stability for an island to the south of Tynagh but there was widespread epeirogenic movement during the mid-Carboniferous and if iron were brought to the sea in such large quantities in just one place we might also expect a high Al_2O_3 content to have accompanied it, yet this is not so.

Conclusions

The trace element data from the wallrocks support Schultz's (1966a) contention that the sulphide-barytes deposit is epigenetic whereas the major element chemistry of the iron-formation supports Derry and coworkers' hypothesis (1965) of an 'exhalative' origin for the iron deposit. Schultz (1966a and b) disagrees with the concept of a contemporaneous origin for the two deposits, pointing out that the ore minerals were deposited in post-lithification fractures and were therefore substantially later than the limestone. But since Shinn (1969) has demonstrated that lithification of carbonate sediments may take place below sea level within a few years of deposition, this argument is not so persuasive.

What is important is the evidence for a mid-Dinantian period of mineralization in the Tynagh area even if the fluids merely contained iron and manganese. Once formed, channelways can be used again and again by mineralizing fluids. It is the period of initiation which is significant for then can a relationship be sought in terms of contemporaneous geological events.

The sulphur isotope results presented by Greig and coworkers (1971) are; δS^{34} in barytes +18 per mille and δS^{34} in sulphides ranging from +3 to -20 per mille. As at Gortdrum the sulphate in barytes may have been derived from residual Lower Carboniferous sea water (Solomon and coworkers 1971) and the sulphide by bacterial reduction of the sulphate to hydrogen sulphide which in turn reacted with hot metal bearing solutions which rose up the fault zone.

VII BRIEF DESCRIPTIONS OF OTHER IMPORTANT POST-CALEDONIAN BASE-METAL DEPOSITS AND GENERAL FEATURES OF THE IRISH ORE BODIES

Abbeytown Mine (Varvill 1959)

Sphalerite, galena and pyrite are disseminated in, and replace, a gently tilted calcareous sandstone 7.3 m thick (the Index Bed). Mineralization also occurs in a lower grit bed as well as in openings related to flexures above and below the Index Bed. The Lower Limestone Group is about 100 m thick but the ore deposits are restricted to a patchily dolomitized zone 40 m thick. The average grade of the ore mined since the war was lead, 1.20% and zinc, 2.58%.

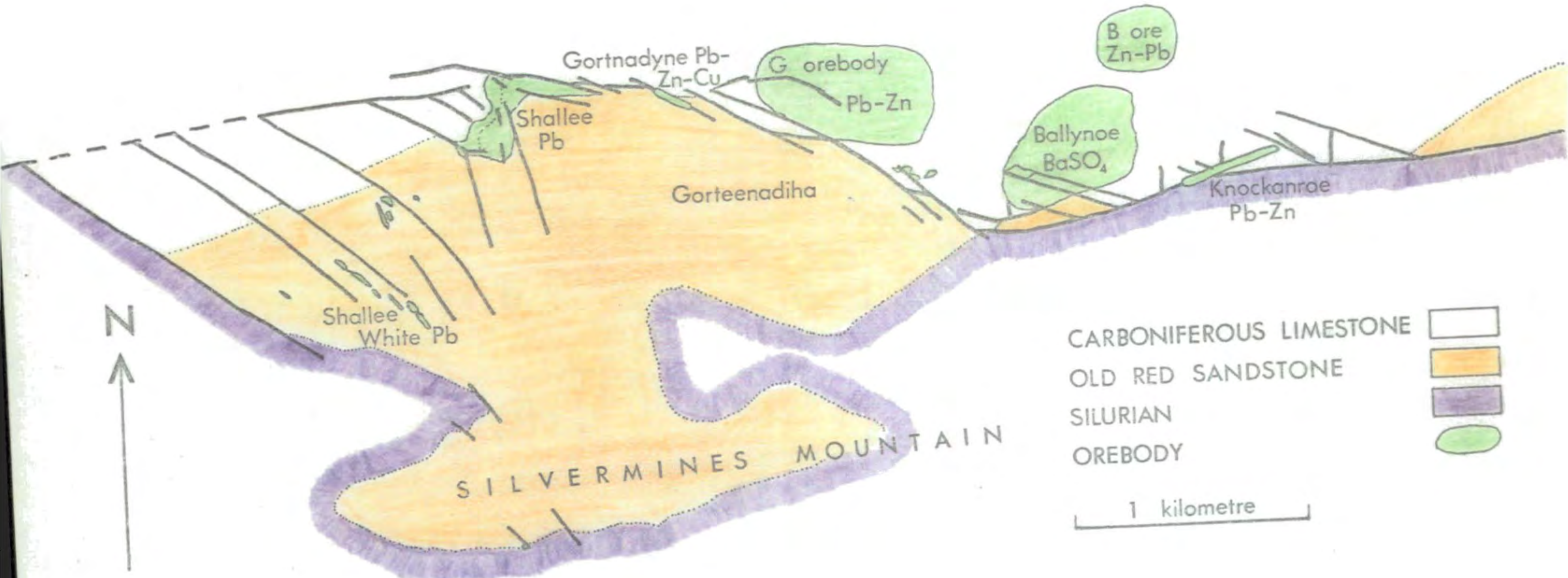
About one million tons of this ore were removed before closure in 1961 (O'Brien 1959). The ore deposit has been worked intermittently since the Middle Ages. Sphalerite predominates over galena in the eastern workings, whereas the opposite is the case in the deeper western workings. Northwards sphalerite and pyrite are enriched below the Index Bed.

A conservative estimate of the original metal content of the ore body may be calculated from the quantity and the grade of the ore presented above. This gives 12,200 tonnes of lead and 26,220 tonnes of zinc; a total of 38,420 tonnes. The original content was probably much higher; substantial quantities may have been removed by marine errosion as well as earlier mining ventures. Moreover, sub-ore grade zinc-lead presumably still remains.

The ore deposit lies between two east-west faults which juxtapose the Lower Limestone Group with schists of Moinian type. These same schists presumably underlie the limestones (Plate 1).

Silvermines (Rhoden 1958)

The Silvermines deposits consist of galena, sphalerite, chalcopyrite,



Gortnadyne Pb-Zn-Cu
G orebody Pb-Zn
B ore Zn-Pb
Shallee Pb
Ballynoe $BaSO_4$
Gorteenadiha
Knockanroe Pb-Zn
Shallee White Pb
N
SILVERMINES MOUNTAIN
CARBONIFEROUS LIMESTONE
OLD RED SANDSTONE
SILURIAN
OREBODY
1 kilometre

Figure 7 - 1

Geological map of the Silvermines district simplified from Rhoden 1958. Positions of the newly discovered 'G' and 'B' ore bodies and the Ballynoe barytes deposit supplied by J Lawlor.

pyrite and barytes extending 3 km along a complex east-west fault and associated eastnortheast and north-south trending faults. Ore is also seen as disseminations in the lower dolomite of Tournaisian age. The Silvermines Main Fault has a throw of between 240 and 340 m to the north and brings Old Red Sandstone as well as the underlying Silurian shales into contact with the Carboniferous Limestone. The largest deposit, however, is the newly discovered pyritic zinc-lead 'G' Upper Zone ore body to the north of the Fault (Figure 7 - 1). This is a stratiform deposit lying between a muddy reef limestone and the overlying dolomite breccia of lower Viséan age. A large strata-bound deposit of cryptocrystalline barytes occurs at the same horizon just to the east at Ballynoe Mine. Gordon-Smith in Snelgrove (1966) suggested that the 'G' orebody and the barytes deposit resulted from sedimentary precipitation of sulphides and sulphates at different redox potentials; the barytes in oxidising conditions and sulphides in a shallow basin with reducing conditions. This thesis has recently been strongly supported by Graham (1970). He shows that sulphur isotope ratios in the barytes deposit are close to those for Lower Carboniferous seawater sulphate whereas sulphur in the sulphides in the Upper 'G' ore body is extremely enriched in the lighter isotope indicating prolific bacterial activity. The metal bearing solutions may have emanated from the east-west fault. Colloform and sedimentary structures are common in the Upper 'G' ore body. A bed of chert and cherty breccia up to 55 m thick overlies the dolomite breccia (Plate 1). Temperatures of mineralizing fluids responsible for the lower (replacement) ore zone have been estimated by fluid inclusion filling temperatures as about 255^{o}C, though ranging from 180^{o}C to 365^{o}C (Greig and coworkers 1971).

The approximate content of ore at Silvermines is lead, 500,000 tonnes; zinc, one million tonnes and barytes about two million tonnes.

Keel

Galena, sphalerite and barytes occur in Silurian banded grits and mudstones, Devonian sandstones and conglomerites and Tournaisian silts, limestones and shales (O'Brien 1966; Patterson in Snelgrove 1966). The massive and disseminated mineralization is associated with an east-west fault which brings Silurian rocks overlain by Old Red Sandstone against sandstones and limestones of Carboniferous age. Two fluid inclusion results indicate temperatures of 175°C, and further work by Watling using trace amounts of mercury and other volatile constituents indicate temperatures of mineralization averaging 220°C with an upper limit of 300°C (Morrissey and coworkers 1971).

A thin sedimentary iron oxide deposit occurs within the lower Viséan limestones (Pers.comm.Patterson 1968; see Plate 1).

The sulphide deposit has a combined lead-zinc content of about 120,000 tonnes.

Glendalough (O'Brien 1959)

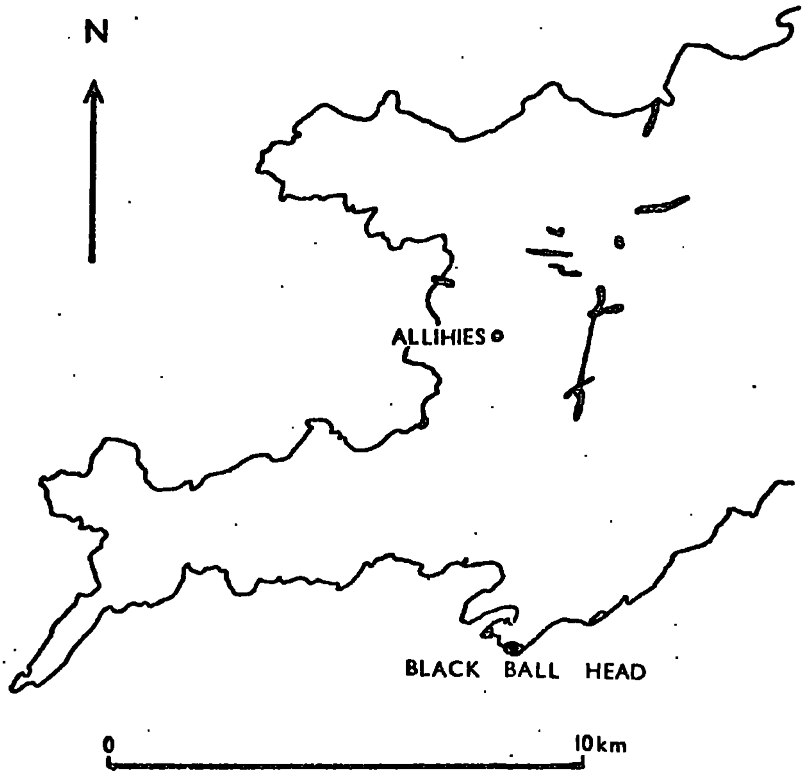
An unusual deposit of lead with zinc was mined from north-south and subsidiary northnortheast and eastnortheast veins in the eastern margin of the Leinster granite batholith. About 50,000 tonnes of lead were removed. No reliable age for the deposit exists, so that it may be late Caledonian or post-Caledonian. If the former then it will not belong to the family of sulphide deposits occurring in the Carboniferous Limestone.

Aherlow (Cameron and Romer 1970)

An east-west vein 600 m long contains chalcopyrite, bornite and chalcocite, with minor sphalerite and galena occurring peripherally to the zone of mineralization. Copper and silver total about 100,000 tonnes and 360 tonnes respectively. Host rocks are muddy bioclastic limestones, and a chert bed of C_1 age about 23 m thick stratigraphically overlies the mineralized zone (Plate 1). Structurally the vein lies in a disturbed portion of the northern limb of the Aherlow syncline 12 km south of Gortdrum.

Navan (O'Brien and Romer 1971)

A very large zinc-lead deposit replaces Carboniferous Limestone near Navan but no detailed description has been made of this deposit to date.



Allihies (Sheridan 1964)

Chalcopyrite in a massive compact quartz gangue occurs in veins trending east and west as well as in one vein running in a north-northeasterly direction. The country rocks are strongly folded Old Red Sandstone sandstones and shales. The axial trend of the folds is westsouthwest-eastnortheast. Coe (1959) has suggested a relationship between intrusive tuffs (coloured red in diagram) outcropping to the south of Allihies and the mineralization (black in diagram). Both the intrusions and the mineralization post date the main folding which probably took place at the end of Carboniferous times.

The mine originally contained at least 50,000 tonnes of copper as calculated from O'Brien's figures (1966).

General Features of the Ore Deposits

The ore deposits in the Irish Carboniferous consist of a low to medium temperature suite of sulphides; sphalerite, galena, pyrite, chalcopyrite, tennantite, tetrahedrite, bornite, chalcocite, often accompanied by barytes. Wall rocks are dolomitized in some cases, although dolomitization is not necessarily accompanied by mineralization. Silver of the order of 0.003% of ore is present in most deposits. Usually the sulphides are fine grained and often intimately mixed. Sphalerite, galena and pyrite exhibit colloform textures in some deposits.

It is possible that the faults trending approximately N 80°E associated with the base metal deposits were active in Lower Carboniferous times; in support of this Derry and coworkers (1965) described some thinning of Lower Carboniferous beds towards the Tynagh Fault. Schultz (1966b) rejected this but the transition from Waulsortian Bank formation through 'pseudo-breccia' of Waulsortian fragments to a deeper water Calp and Ironstone from south to north implies some concomitant movement. Weber (1964) has also suggested that there was some movement along the Silvermines Fault in Lower Carboniferous times as evidencedby the northward slumping of sediments across the present site of the Fault. The fault at Gortdrum was probably in existence in the Lower Viséan as evidenced by the distribution of intrusive rocks. The spasmodic occurrences of calcareous sandstones at Abbeytown imply mid-Dinantian movements along the Ox Mountains and associated faults. Major movements along these faults were of a later date.

There is no evidence to suggest one source of ore at depth for all the deposits; rather zoning within some mines, for example Tynagh and Gortdrum, points to an individual source for each area of mineralization.

The study of trace element aureoles to the Tynagh, Gortdrum, Oola, Carrickittle and Ballyvergin base-metal deposits forces the conclusion that they are all epigenetic. Nevertheless the Tynagh chert hematite sediment is probably 'exhalative' implying a late Tournaisian age for the onset of mineralization in that deposit. Likewise if we accept the syngenetic interpretation of the Silvermines upper 'G' orebody then mineralization there too started in the late Tournaisian. A thick sequence of chert and cherty breccia overlying the 'G' orebody may be the result of silica deposition from spent mineralizing solutions that escaped onto the sea-floor. The chert at Aherlow is late Tournaisian and may have a similar origin. It is true that thin chert bands and nodules are ubiquitous in Ireland but are normally developed only in Z_2 and D beds apart from the cherty limestone (S_1) in the Pallas Green volcanic sequence. The idea that the cherts may be 'exhalitive' is prompted by the presence of chert at Tynagh but further research into genetic relationships between the 'sedimentary' cherts and the sulphides is required.

The thin sedimentary iron deposit occurring in lower Viséan limestone at Keel is reminiscent of the Tynagh association.

That four of the seven most important deposits occupying Carboniferous rocks in Ireland are associated with what may be 'exhalative' sediments leads me to conclude tentatively a late Tournaisian-early Viséan age for the onset of the post-Caledonian mineralization in Ireland.

Recent model lead ages ranging from 270 my to 70 my (Greig and coworkers 1971) are not considered, as generally they are not thought to have an exact significant (Richards 1971). Disagreements of as much as 300 my are to be expected between derived single stage model ages and the true age.

Although the mineralization and the Carboniferous volcanic activity appear to have been partly contemporaneous there is no direct genetic link between the two phenomena (See Figure 1 - 1). Nor are there any obvious relationships between palaeogeography and mineralization (See Figures 2 - 1 and 2 - 2); a conclusion consistent with the trace element results. The deposits occupying Carboniferous Limestone are not aligned as one might expect in relation to Armorican structures although they probably have a Hercynian age.

The medium temperatures of ore deposition preclude theories of origin of the major deposits involving derivation of mineralizing solutions from Carboniferous basins as they were not more than 5000 m deep in the Central Plain. Moreover the present maximum depths of basins near Tynagh, Silvermines and Keel are of the order of 1000 m or less.

The trace element aureoles appear to be of two kinds which correspond to the ore body types. The copper deposits in Lower Limestone Shales and Lower Limestones, Ballyvergin and Gortdrum, are surrounded by an arsenic and lead high. A variety of elements are also enriched in the wallrocks to the lead, zinc, (copper) deposits in Waulsortian limestones, Tynagh and Carrickittle but only manganese forms an extensive and consistent halo. In the case of Tynagh there may be an extensive syngenetic manganese aureole, but this requires further work.

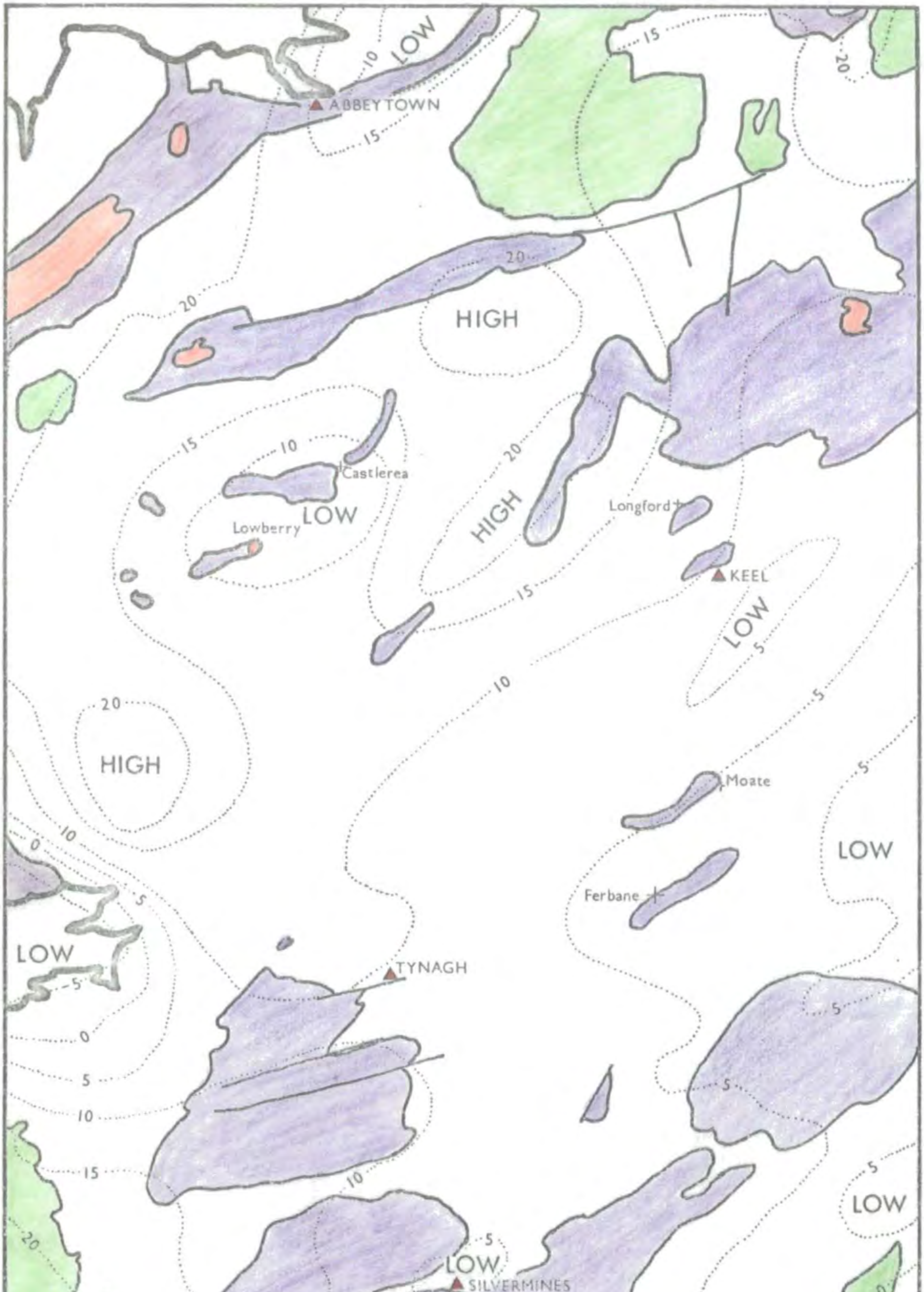
Sulphur isotope studies may be interpreted as implying a sulphate sulphur derivation from Lower Carboniferous sulphatic connate waters. Sulphide sulphur may have been reduced from the sulphate although a juvenile origin has also been suggested (Greig and coworkers 1971).

VIII TECTONIC CONTROLS OF MINERALIZATION

Introduction

Working in Ireland in the middle sixties it was difficult not to think in terms of prospecting for new deposits. An attractive area was the bog covered plain north of Tynagh where ores may have been easily overlooked in the past for lack of outcrop. Professor Dunham had pointed out to me that mineralization often appeared to be spatially related to basement highs which sometimes owed their existence to granites. This being so, a normal approach to prospecting was to isolate gravity lows on a Bouguer Anomaly map. Murphy's 1952 map showed that most of the ore bodies appeared to lie close to gravity lows (Figure 8 - 1). Another common feature remarked on in the previous chapter was the coincidence of ore bodies with the approximately east-west faulted contacts of Old Red Sandstone with Dinantian calcareous rocks. Most of these faults have a downthrow to the north. A gravity low related to an acid intrusive was noticeable at Lowberry near the county boundaries of Roscommon, Galway and Mayo (Figure 8 - 1). The northern part of this anomaly coincided with an Old Red Sandstone inlier elongated east and west of which the northern junction with Dinantian rocks looked most attractive from an exploration point of view.

As soon as I decided to investigate this area I realised that it lay along the northerly projection of a line through Gortdrum, Silvermines and Tynagh. This line could also be extended to Abbeytown, and three Old Red Sandstone or Lower Carboniferous sandstone inliers appeared to abut, but not cross it (Figures 8 - 1 and 8 - 2). Castlerea seemed to lie in a structural depression with an inlier to the northeast and west. I remembered that the continental margin to the west of Ireland has a north-south trend, that is, parallel to the line drawn through the deposits. This parallelism suggested a possible relationship between continental break up and mineralization.



LOW
10
ABBEY TOWN
15
20
HIGH
20
15
10
Castlerea
LOW
Lowberry
20
HIGH
15
Longford
KEEL
LOW
5
10
5
20
HIGH
Moate
10
0
5
LOW
Ferbane
LOW
-5
TYNAGH
0
5
5
10
5
15
10
5
LOW
20
5
LOW
SILVERMINES
0

Figure 8 - 1

Diagram to illustrate the reason for interest in the Castlerea area as a possibility for mineral exploration. Geology from the Geological Survey of Ireland 1:750,000 geological map 3rd edn.

Purple:	rocks of pre Carboniferous Limestone age
Red:	granites and felsites
White:	Carboniferous Limestone
Green:	rocks of post Carboniferous Limestone age
Red triangles:	major mineral deposits

Bouguer anomaly contours in mgals from Murphy 1952

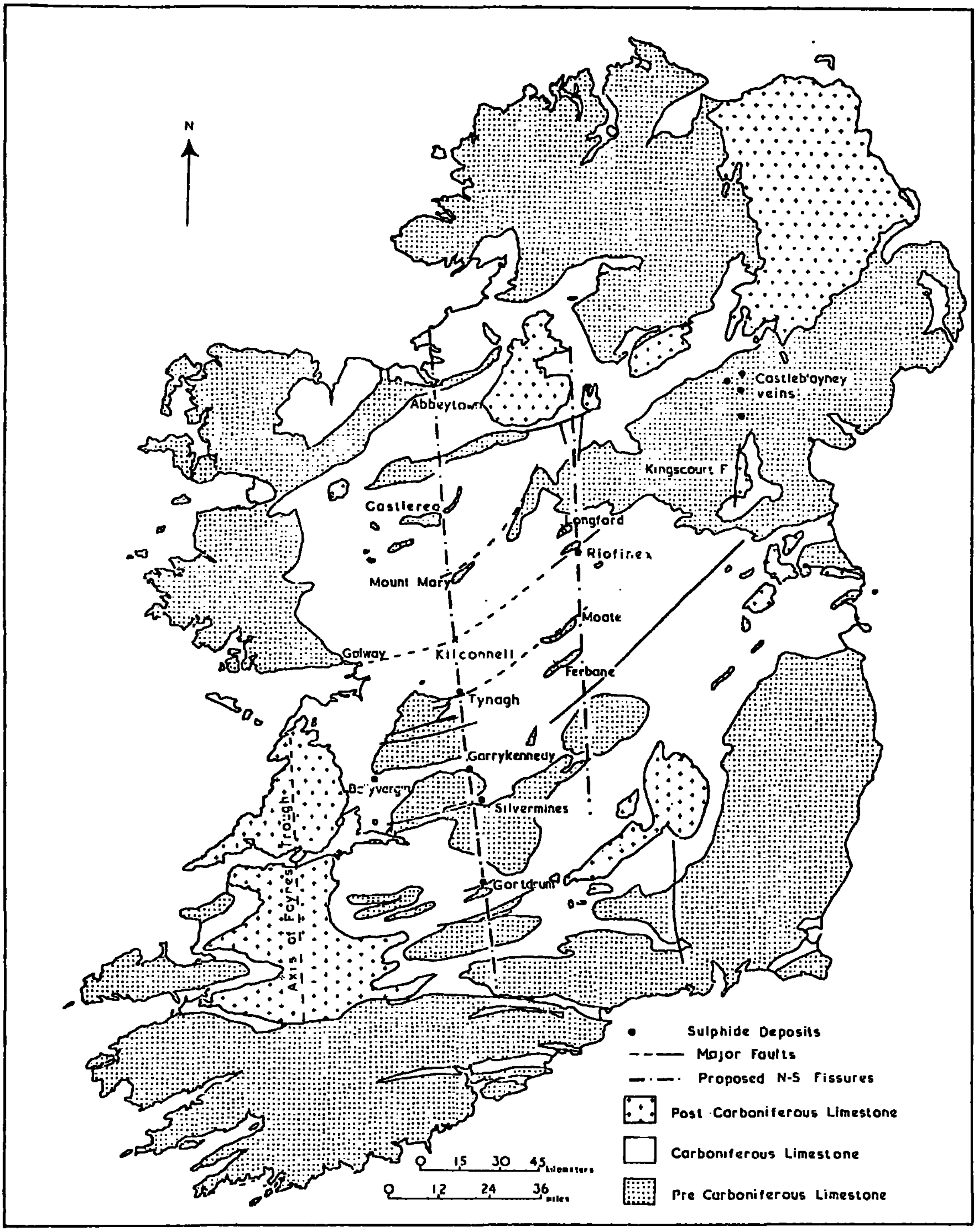
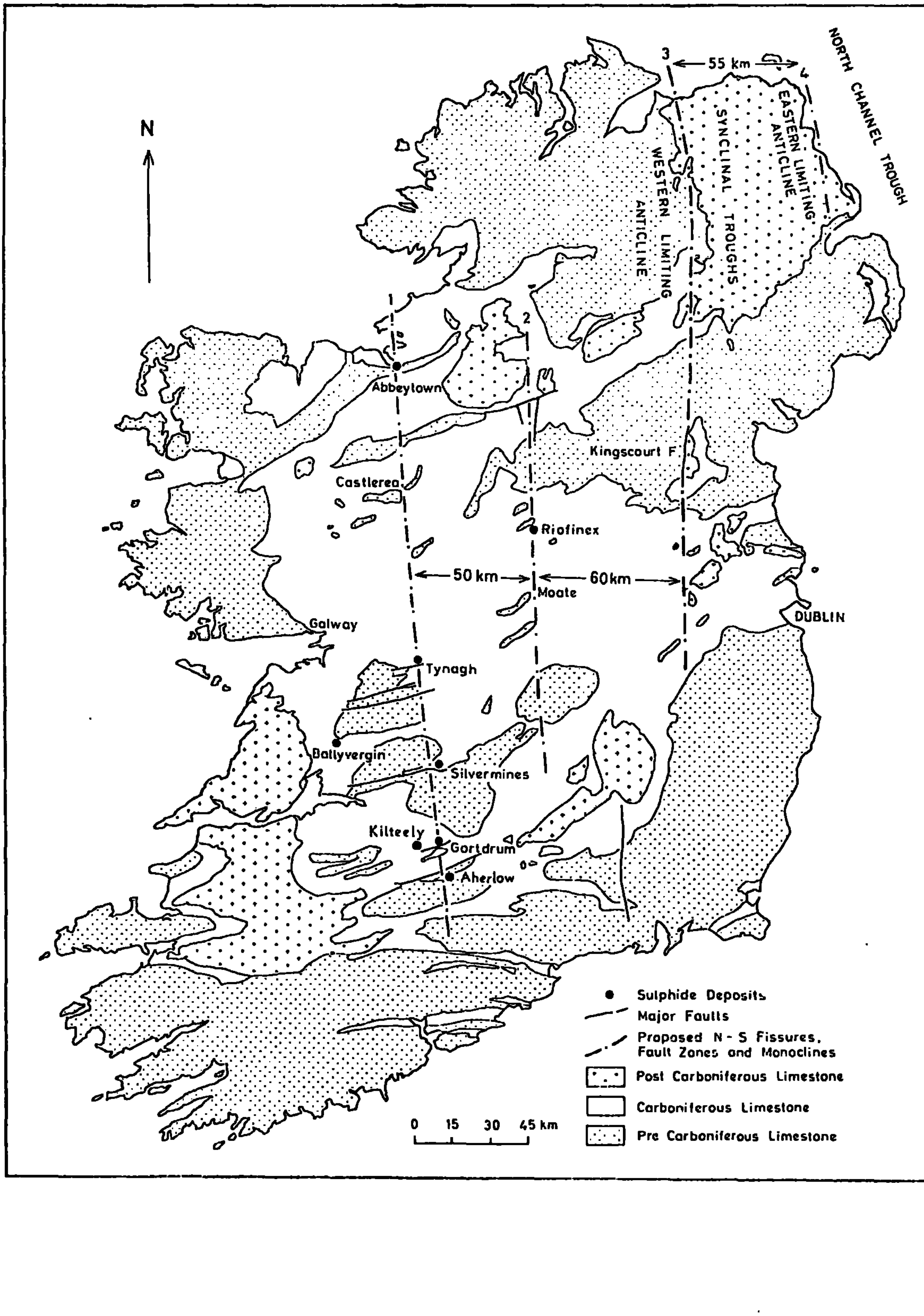

N
Abbeytown
Castlerea
Mount Mary
Galway
Kilconnell
Longford
Riofinex
Moate
Ferbane
Tynagh
Garrykenneay
Silvermines
Gortdrum
Castleblayney veins
Kingscourt F
Axis of Foynes Trough
Sulphide Deposits
Major Faults
Proposed N-S Fissures
Post Carboniferous Limestone
Carboniferous Limestone
Pre Carboniferous Limestone
0 15 30 45 kilometers
0 12 24 36 miles

Figure 8 - 2

Copy of map published in 1968 (Russell 1968). It was suggested that the Kingscourt Fault and Castleblayney veins may have been the surface manifestation of another north-south 'fissure' and that the Ballyvergin deposit could also relate to a 'fissure'. No evidence for a north-south geofracture through Ballyvergin has been found and this idea has been rejected. Gardiner (1969) pointed out that the name of Foynes had previously been used in a description of an east-west trough in which a thickening of Namurian sediments had been demonstrated (Hodson and Lewarne 1961). There is no available evidence regarding a possible thickening along a north-south axis in this region at that time. Nevertheless, a series of east-west synclines do appear to have a north-south distribution in western Ireland and this may be significant in terms of the east-west tension theory, but the name Foynes Trough on this map is erroneous. O'Brien (1969) criticized the length of the Keel (Riofinex)-Ferbane line, pointing out that only the central 50 km of the line had a supporting argument in the text. Extension of the line northwards to a small rift but not beyond is feasible. The southerly extension was made on the strength of a private communication regarding the discovery of mineralization. No major deposit apparently has been discovered, however, and this line should not extend further south than the Ferbane inlier



N
3
55 km
4
NORTH CHANNEL TROUGH
EASTERN LIMITING ANTICLINE
SYNCLINAL TROUGHS
WESTERN LIMITING ANTICLINE
1
2
Abbeytown
Castlerea
Kingscourt F.
Riofinex
50 km
60 km
Moate
DUBLIN
Galway
Tynagh
Ballyvergin
Silvermines
Kilteely
Gortdrum
Aherlow
Sulphide Deposits
Major Faults
Proposed N - S Fissures, Fault Zones and Monoclines
Post Carboniferous Limestone
Carboniferous Limestone
Pre Carboniferous Limestone
0 15 30 45 km

Figure 8 - 3

Copy of map published in 1969 (Russell 1969). The Kingscourt geofracture has been added (see text). The copper deposit at Aherlow was announced in 1969 (World Mining 22 no 2 1969 p 83) and is shown, but I had previously heard of the exploration in that area which predated the formulation of the geofracture theory. The geofracture marked 4 was taken from Wright (1919). Evidence for this structure is weak and it is not discussed further in the text.

Although no geological reality could be given to this line many structures in Ireland were seen to have meridional trends, including the outlines of Ireland itself. The Riofinex deposit at Keel lay adjacent to one of four Old Red Sandstone inliers distributed north and south about fifty kilometres east of the line drawn from Abbeytown to Gortdrum (Figure 8 - 2). East of this again, the Kingscourt Fault was seen to trend north-south and an extrapolation of this fault line north intersected the Castleblayney veins (Cole 1922) and then on to one of Wright's postulated structural units (Wright 1919) pictured by Charlesworth (1963) (Figures 8 - 2 and 8 - 3).

In order to give these lines geological credibility, it was necessary to relate them approximately to the time of continental rifting and drifting and also to explain how mineralization could be caused by a linear control.

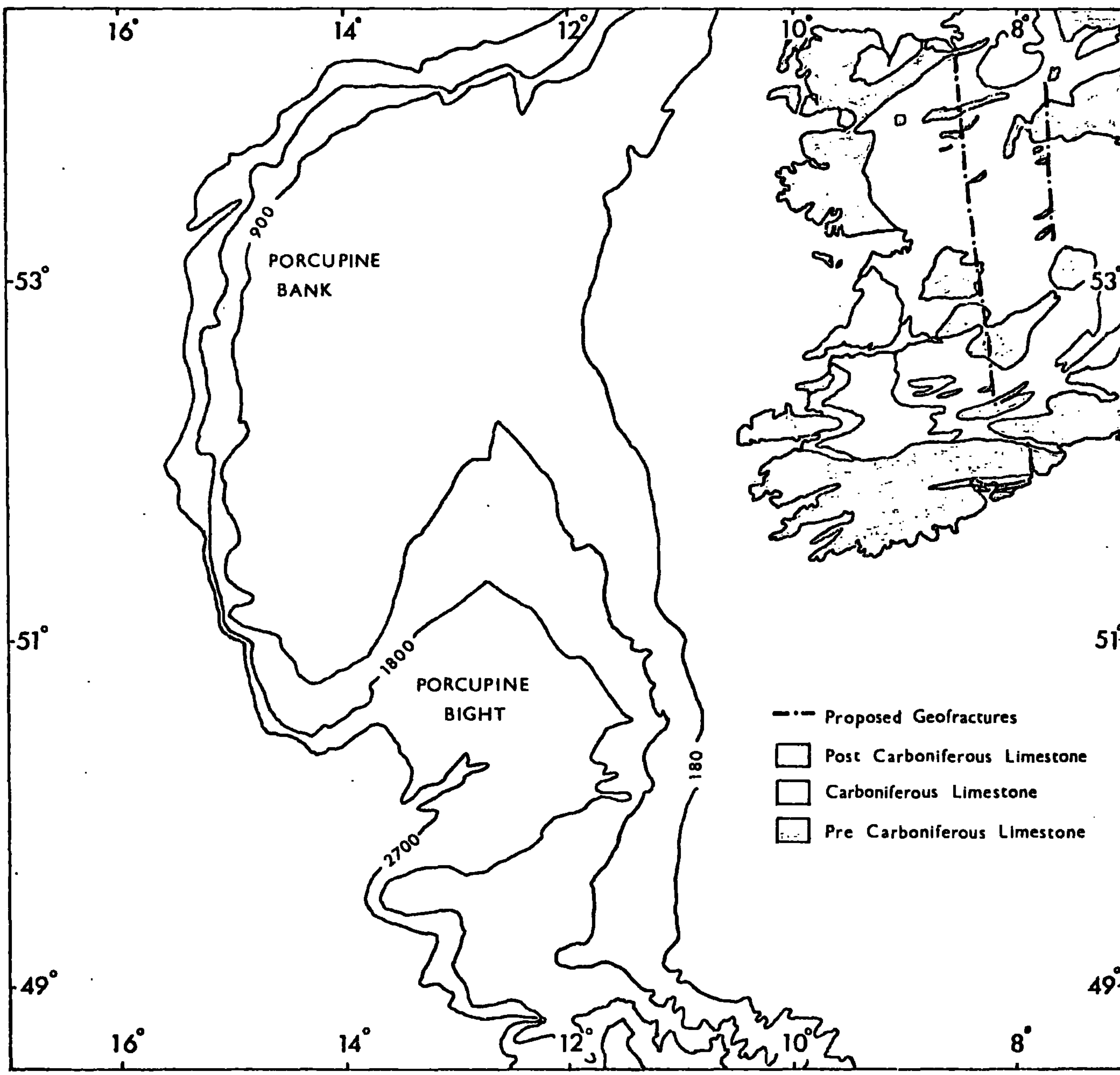
Regarding the first point, most geologists and geophysicists considered continental fragmentation in the North Atlantic region to have taken place in late Mesozoic or early Tertiary times. Westoll (1965), however, favoured an earlier break up, the first movements of which he considered to be evidenced by movement along the Great Glen Fault in Scotland between Lower and Middle Old Red Sandstone times (Kennedy 1946). I used his suggestion as support for east-west tension in Devonian-Carboniferous times which I suggested also caused north-south fissuring in the mid-Dinantian (Russell 1968), this in turn controlling the siting of the mineral deposits. The original maps showing the postulated north-south controls (Russell 1968; 1969) are presented in Figures 8 - 2 and 8 - 3.

The second point was solved by assuming magma to have risen along these fissures to a high level in the crust and perhaps occasionally to the surface thus explaining the tuffs in the Tynagh deposit. Intrusions centred on intersections between the fissures and east-west faults were thought to have acted as 'hot spots' giving rise to a convective or partial convective system within pore waters in the Lower Palaeozoic geosynclinal rocks. The pore waters dissolved out metals from the Lower Palaeozoic sediments and reprecipitated them in hospitable rocks near the surface or on the sea floor.

I now consider both these suggestions to be erroneous and in this chapter I outline an updated version of a theory that is capable of explaining the genesis and siting of mineral deposits in Ireland.

General Statement

Abbeytown, Tynagh, Silvermines, Gortdrum and Aherlow sulphide deposits are distributed along an approximately north-south line trending N 7° W (the Abbeytown-Gortdrum line). Adjacent to this line are Old Red Sandstone inliers at Mount Mary and Castlerea (Russell 1968; 1969). The Riofinex sulphide deposit at Keel 50 kilometres to the east of the north-south line mentioned above is also spatially related to an Old Red Sandstone inlier. A line drawn approximately parallel to the Abbeytown-Gortdrum line through the Riofinex deposit and adjacent to the western extremities of three other Old Red Sandstone inliers near Longford, Moate and Ferbane runs N 3° W. This line bisects a small rift 50 km to the north of Keel. No other features suggest a continuation of a linear peculiarity to the north of this small rift or to the south of the Ferbane inlier. About 60 km to the east of the Keel--Ferbane line an important north-south trending fault (the Kingscourt Fault) occupies the central portion of a north-south structure 200 km in length (Figure 8 - 3). Jackson (1955) has demonstrated that the vertical throw of the Kingscourt Fault was one kilometre in Dinantian times. Subsequent movements totalled more than another kilometre. The Castleblayney veins may lie on the northerly extension of this Fault (Figure 8 - 2). To the north of these veins Wright (1919) postulated a north-south fold as the western margin of a trough and two synclines, the presence of which have been endorsed geophysically (Cook and Murphy 1952 and see Bullerwell 1967). Although Wright regarded the folds in the



16°
14°
12°
10°
8°
53°
51°
49°
900
PORCUPINE
BANK
1800
PORCUPINE
BIGHT
2700
180
Proposed Geofractures
Post Carboniferous Limestone
Carboniferous Limestone
Pre Carboniferous Limestone

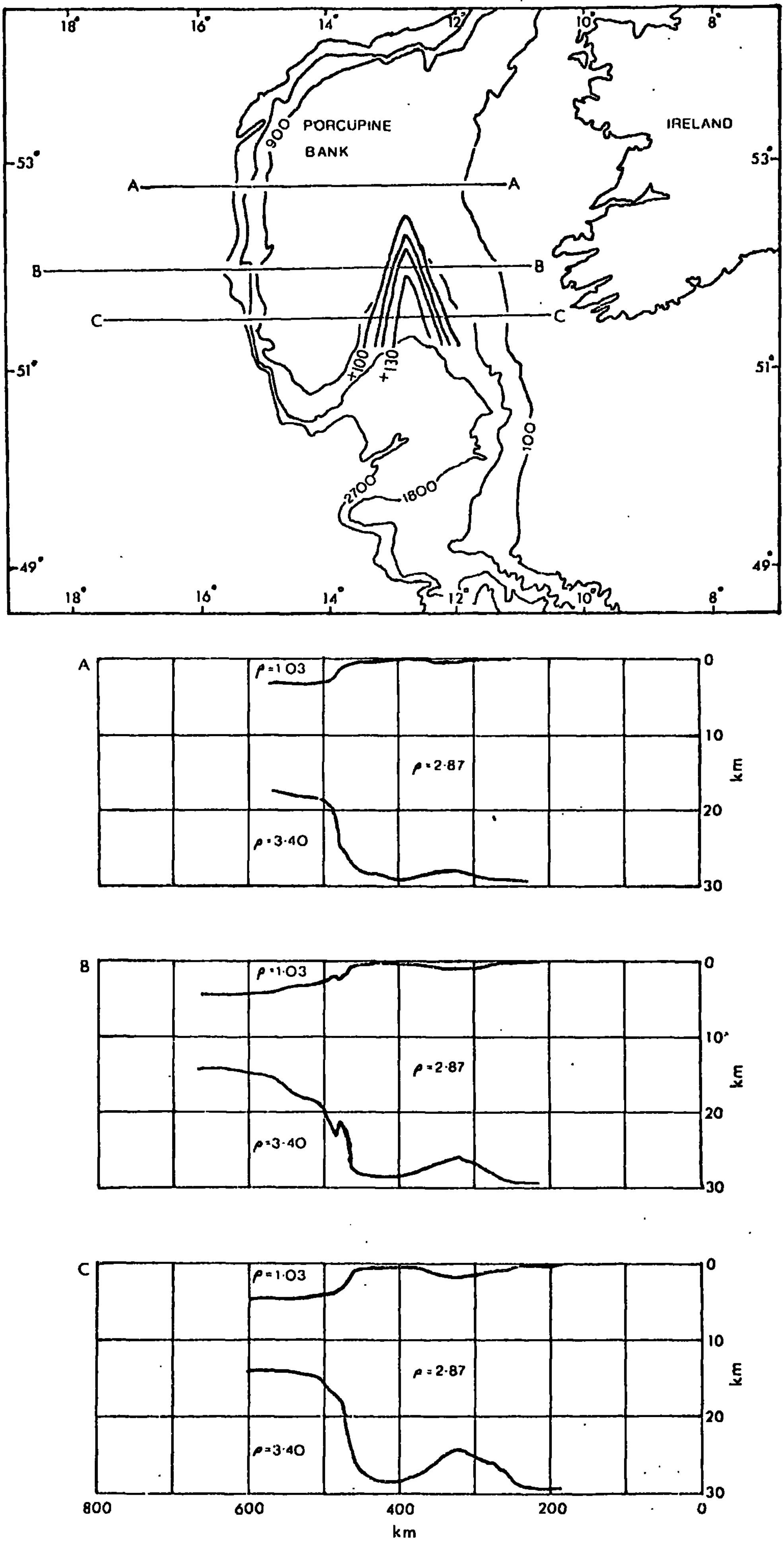
Figure 8 - 4

Copy of map published in 1968 (Russell 1968) showing the submarine topography west of Ireland and its relationship to the geology of Ireland and proposed north-south 'fissures'. (Bathymetry in fathoms from National Institute of Oceanography Maps, Area 16).

Mesozoic rocks as being superimposed on steeper folds in the Carboniferous strata, there is no evidence of Upper Palaeozoic basins in northeast Ireland. Viewed in detail, Wright's western limiting anticline deviates to a northnorthwest trend in the north. Fowler and Robbie (1961) drew attention to a sharp correlation between the Drumkee Fault, with a throw of 1070 m to the east, and the gravity anomalies. North of the Drumkee Fault a group of faults having the appearance of tension fractures due to folding, trend northnortheast and northnorthwest. To the north again, the Killymoon Fault trends north-south and has an easterly throw of 120 m. On the downthrow side of this fault the Carboniferous Limestone dips 60^{o} to the east. The north-south structure also continues to the south of the Kingscourt Fault as evidenced by a meridional trend to the Bouguer anomaly contours (Murphy 1962b), and the distribution of Namurian rocks (Figure 8 - 2). I suggest that the structures described above are part of a major north-south geofracture (3 in Figure 8 - 3), 200 km long, with normal fault characteristics.

The major structural trends, except in the extreme south of Ireland, are Caledonoid and north-south. The distribution of major sulphide deposits appears to be governed by these same trends.

Most of the structures in Ireland have previously been related to Caledonian and Armorican earth movements. The Armorican disturbance is envisaged as giving rise to east-west structures in the south and reactivating structures parallel and normal to Caledonian trends elsewhere. These movements do not adequately explain the many north-south features which include faults, monoclines and the predominant joint direction. To the west and north of Ireland certain major submarine features are also predominantly north-south, for example the western edge of the Porcupine Bank (Figure 8 - 4) and part of the eastern margin of Rockall Trough (Figure 9 - 4). Andrew Stacey also pointed out to me that a gravity survey by himself and



18°
16°
14°
12°
10°
8°
53°
51°
49°
PORCUPINE
BANK
IRELAND
900
A
B
C
+100
+130
2700
1800
100
ρ=1·03
ρ=2·87
ρ=3·40
0
10
20
30
km
800
600
400
200
0
km

Figure 8 - 5

Bouguer anomaly map of Porcupine Bight and isostatic models for the continental margin west of Ireland calculated from observed Free-Air anomalies. (Copied from Gray and Stacey (1970)).

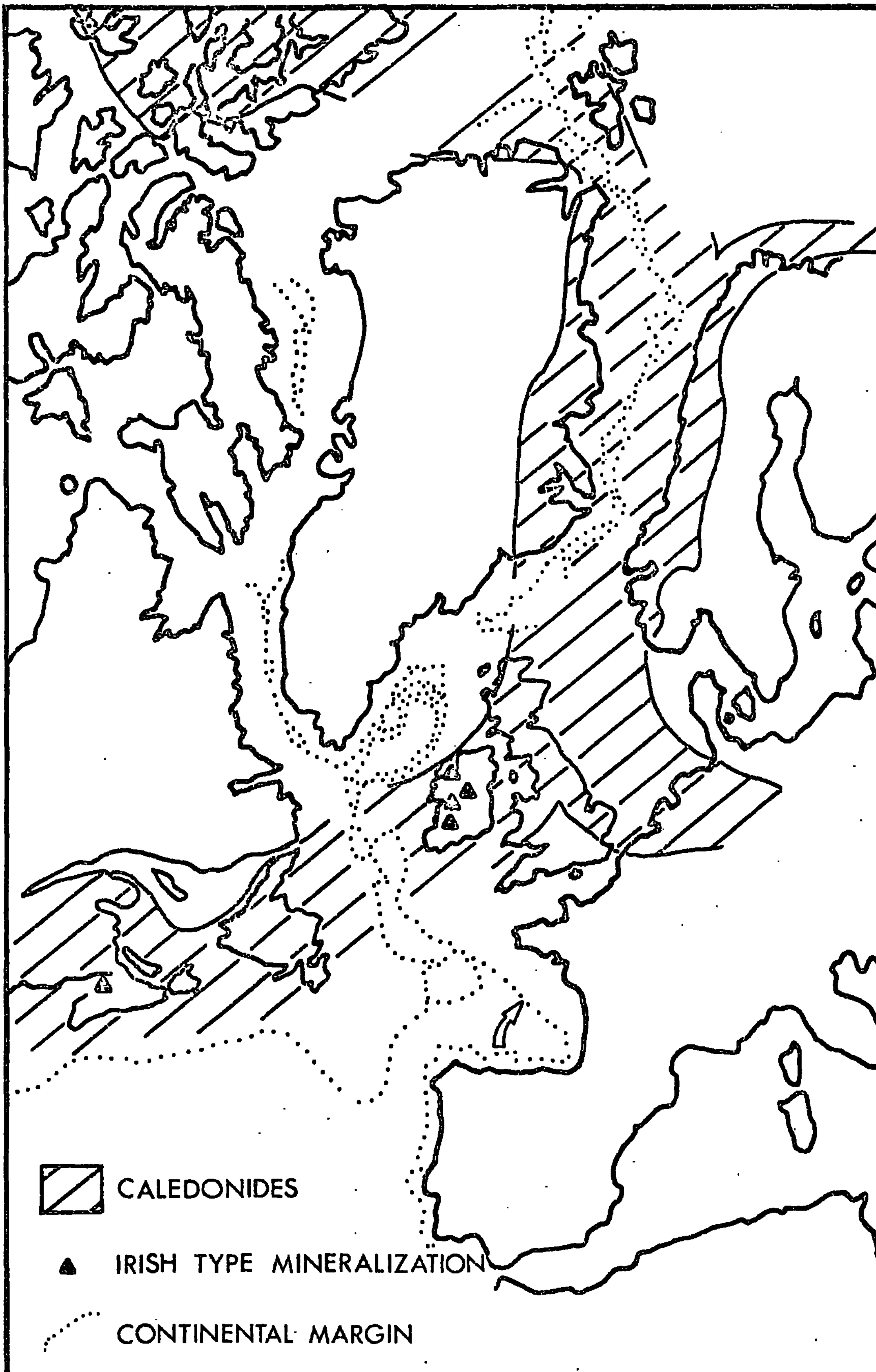

CALEDONIDES
IRISH TYPE MINERALIZATION
CONTINENTAL MARGIN

Figure 8 - 6

Reconstruction of the North Atlantic continents before drift (Bullard, Everett and Smith 1965) illustrating the relationship of Irish-type mineralization to the continental margins and the Caledonian-Appalachian geosynclinal rocks (Fitch 1965). Modified from Russell 1968.

Gray had revealed a steep gradient trending north-south associated with the western margin of Porcupine Bank and also that the strike of the maximum gravity anomaly off the west coast of Ireland is N 8^{o} W. Gray and Stacey (1970) have since published their results and show 'Free-Air' anomalies with north-south trends to progressively mask the affects of the Caledonian fold belts towards the continental margin (Figure 8 - 5).

Mineral deposits similar to those discussed here occur in the Maritime Provinces of eastern Canada, the largest being at Walton, Nova Scotia (Figure 8 - 6). In the Walton area rocks underlying the Carboniferous are slates, argillites and quartzites of the Meguma Series, of Lower Palaeozoic age (Taylor 1965). Lower Carboniferous sandstones, shales, ferruginous limestones and conglomerates of the Horton and Cheverie Formations lie with strong unconformity on the Meguma Series. Boyle (1963) noted the generally high sulphur, lead, zinc, copper and barium contents of the Horton-Cheverie Formations. According to Bell (1929) these rocks are equivalent to limestones, shales and sandstones of Tournaisian age in Ireland. Fissile limestones, limestone conglomerates and shales of the Windsor Group, which correspond to the Viséan rocks of Ireland, overlie the Horton-Cheverie Formations.

The barium-lead-zinc-silver deposit at Walton consists of fine-grained sphalerite and galena overlain by cryptocrystalline barytes. It is approximately stratiform and was formed by replacement and fracture filling of the lower Windsor limestones and the underlying Cheverie sandstones and shales (Boyle 1963; Boyle and Jambor 1966). The deposit is localized in a brecciated zone at the intersection of two major fault zones trending east-west and northeast-southwest. The age of mineralization is unknown, but the stratigraphic and structural location of the deposit is similar to that of the Irish ore bodies.

Numerous smaller deposits occur along a major fault zone trending due east from Walton (McCartney and McLeod 1965). This direction parallels the continental margin and the faulting may have been caused by a stress field that finally led to the splitting apart of Africa from the Maritime Provinces. The fault zone, however, also parallels the Appalachian trend and other mechanisms may explain it. Howie and Cumming (1963) point out that fragmentation and subsequent tilting of basement blocks during the Carboniferous would have led to isostatic adjustments, subsequent erosion, and then deposition of thick terrestrial sediments in localized narrow troughs which trend approximately east-west and northnortheast.

Age of Geofractures

The Abbeytown-Gortdrum and the Keel-Ferbane geofractures (geofractures 1 and 2) do not exert a significant control on sedimentation and it is impossible to assign a stratigraphic age to them on this basis. The age of the mineralization is therefore crucial. We have seen that at least the last stages of mineralization post dated Tournaisian sedimentation and in some cases were later than Viséan. Schultz (1968) thought the mineralization at Tynagh was not earlier than Stephanian and possibly later. Rhoden (1958) favoured a Triassic or early Jurasaic age for the mineralization at Silvermines.

It is important, however, to date the earliest phase of mineralization as this may have been related to the initiation of the postulated geofractures. As mentioned in chapters VI and VII there are arguments for a mid-Dinantian age of mineralization at Tynagh, Silvermines and less certainly at Keel and Aherlow.

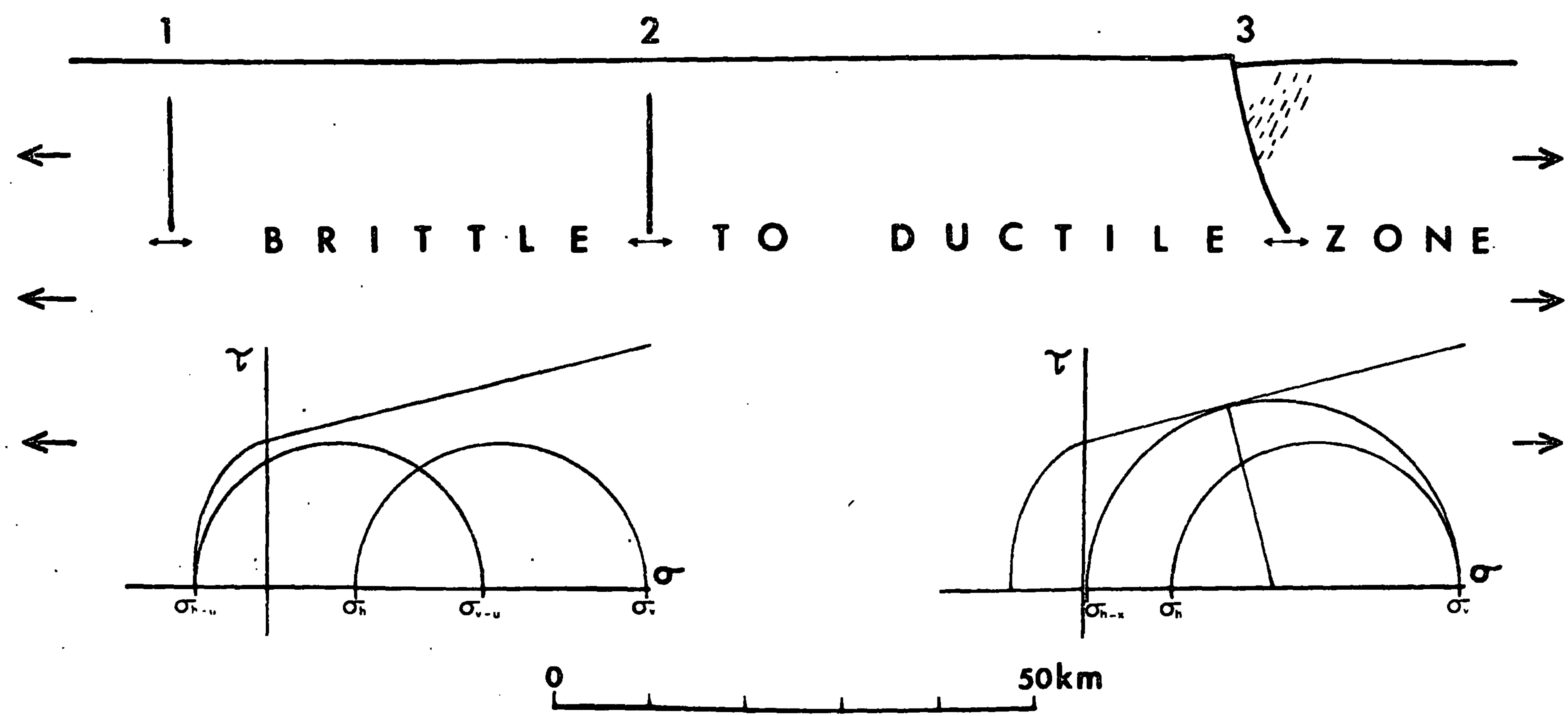
The third geofracture comprising the Kingscourt Fault can be given an approximate age by stratigraphic means. This was pointed out to me by Dr John Jackson. In his thesis (1955) on the Kingscourt area he demonstrated that the Fault itself affected upper Dinantian sedimentation. As remarked above, he estimated that the vertical throw of this Fault was one kilometre in Dinantian times. There is no evidence regarding the presence of the Fault previous to this time.

From this sparse evidence I tentatively suggest that geofracturing began towards the end of Tournaisian times. Such an age coincides with the beginning of the Carboniferous volcanic activity in Scotland (Francis 1967). Similar magmatism is less well represented in Ireland but is of approximately the same age.

Mechanism of Formation of North-south Geofractures

The north-south trending fault component of the Kingscourt geofracture is best explained as being the result of a horizontal tensile stress acting in Carboniferous times. Bearing in mind that the trends of portions of the continental margin west of the British Isles are also north-south, it is inductively argued that the three north-south geofractures were formed in response to a horizontal tensile stress field oriented east and west relative to the present pole. We would expect normal faulting as a consequence of such a stress field and yet this type of failure is apparent only in the north and central parts of the Kingscourt geofracture. Elsewhere, the geofractures are presumably vertical tension fractures. A difficulty with the tension fracture postulate is that a state of tension was not thought possible more than a few kilometres below the surface (Anderson 1951) but the geofractures formed independently of the Caledonoid structures implying that they extend upwards from the mechanically homogeneous lower crust.

In this context, prompted by Hubbert and Rubey's (1959) application of the effect of pore pressures to explain overthrusting, Burgess (1969) suggested that tension fractures could form in the brittle-to-ductile zone in the crust if pore pressures were high. Experimental studies of rock deformation (Griggs and Handin 1960; Heard 1960)



1
2
3
BRITTLE TO DUCTILE ZONE
τ
σ
σ_{h-u}
σ_h
σ_{v-u}
σ_v
τ
σ
σ_{h-x}
σ_h
σ_v
0
50km

Figure 8 - 7

Diagrammatic representation of the proposed model for the formation of geofractures in Ireland in the Lower Carboniferous, showing west to east section through the upper lithosphere which is being subjected to a horizontal tensile stress (large arrows). In the west and central region the pore fluid pressures increase in the brittle to ductile zone by an amount u, effectively lowering the hydrostatic stress by the same amount, thus driving a Mohr stress circle of small diameter ($\bar{\sigma}_v - \bar{\sigma}_h$ where $\bar{\sigma}_v$ is the earlier vertical effective and major principal stress and $\bar{\sigma}_h$ is the earlier horizontal effective and minor principal stress) against the failure envelope at a point where it crosses the normal stress (σ) axis so that tensile fractures form with the plane of rupture perpendicular to the minor principal stress (see Secor 1965 and Burgess 1969). Nearer the surface, as pore fluids gain access and escape up and along permeable cross structures, pore pressures drop and the stress circle retreats to the right despite a drop in tensile strength, so that geofractures 1 and 2 do not reach the surface (Russell 1969).

No increase in pore pressures occurs in the region to the east so a similar type of failure cannot take place. Instead, at a correspondingly greater distance from geofracture 2 the horizontal compressive stress $\bar{\sigma}_h$ is reduced by an amount x so that the Mohr stress circle of relatively large diameter touches the fracture envelope to the right of the shearing stress (τ) axis and normal fault compressive failure results. The double headed arrows signify the tensile stress concentrations associated with the bottom of the geofractures which attract fluids from a degassing mantle (cf Orowan 1969), so concentrating the heat required to drive the hydrothermal systems (cf Bailey 1970).

indicate by inference a depth of 15 to 20 km for the brittle-to-ductile transition zone. This zone may have been shallower in the Lower Carboniferous in the area under discussion due to a relatively high geothermal gradient as evidenced by volcanic activity. Secor (1965) has also calculated that theoretically tension fractures can develop at increasingly greater depths in the Earth as the ratio of fluid pressure to overburden weight approaches one.

With this theoretical support geofractures 1 and 2 are considered to be tension joints, though on a very large scale, with a spacing of about 50 km formed as a consequence of east-west relative tension and high pore fluid pressures (Figure 8 - 7). As the tension fractures propagated upwards, the high fluid pressures would have been released when the fluids escaped along permeable cross structures at higher crustal levels; the rocks near the surface were apparently generally strong enough to withstand the surviving tensile stress. This picture explains the relationship of ore deposits to cross-faults and the general absence of north-south zones of failure in the Lower Carboniferous rocks.

In contrast geofracture 3 exhibits normal fault characteristics along its north and central portions and this shear fracture presumably formed in a region where pore pressures were comparatively low. As rocks in the brittle crust are stronger in compression than tension, a correspondingly greater reduction in the horizontal compressive stress would be necessary to induce failure which may explain the relatively large, 65 km separation between this structure and geofracture 2 (Figure 8 - 7).

The high pore fluid pressures invoked to explain the assumed verticality of geofractures 1 and 2 could have originated by degassing of a rising column of mantle (Hess 1962; Nicholls 1965); an idea provided with an experimental basis by Sclar (1970). Alternatively, rising geoisotherms could have freed water from OH-bearing minerals at depth.

TABLE 8 - 1 MINOR-ELEMENT CONCENTRATIONS IN SOME LOWER PALAEOZOIC ROCKS FROM IRELAND (PARTS PER MILLION)

34 Samples of Shales and Greywackes

	Pb	Zn	Cu	Ba
Range	< 17-71	8-288	< 8-82	111-1270
Mean	22	109	51	697
Standard deviation	±16	±53	±19	±58

Experimental precision on ten replicate determinations

	Pb	Zn	Cu	Ba
Mean	20	105	57	720
Standard deviation	±4	±2	±4	±27
Relative deviation	20%	2.2%	7.0%	3.8%

29 samples of volcanics and intrusives

	Pb	Zn	Cu
Range	< 15-62	5-130	< 5-82
Mean	∽18	69	24
Standard deviation	±14	±42	±22

Experimental precision on ten replicate determinations

	Pb	Zn	Cu
Mean	33	18	5
Standard deviation	±4	±2	±2
Relative deviation	12.4%	9.8%	38%
G_1 analyses	51	52	17
G_1 recommended (Fleischer 1965)	49	45	13
W_1 analyses	∽7	82	124
W_1 recommended (Fleischer 1965)	8	82	110

Order of magnitude of concentration, presuming that the sediments make up 80% of the Lower Palaeozoic rocks

Pb	Zn	Cu	Ba
20	100	45	(700)

Speculations on Ore Genesis

The fluids which supplied the metals to the sulphide deposits were possibly highly saline brines (Morrissey and coworkers 1971) but their origin is unknown. It is possible that the metals themselves were leached from the underlying geosynclinal rocks. To establish the feasibility of this idea 63 samples of Ordovician and Silurian sediments and volcanics were collected throughout Ireland away from known mineralized areas and analyzed for lead, zinc, copper and in the case of the sediments, barium (Russell 1968). The results of these analyses are presented in Table 8 - 1 with precision data and analyses of the standard rocks G_1 and W_1. The standard deviations from the mean values are high and the results of this reconnaissance survey demonstrate only the general order of magnitude of trace elements in these rocks. Silver was not determined, but Taylor (1965) quoted a Clarke value in greywackes and shales of 0.05 ppm and a similar value is assumed for these sediments. Greywackes and silts constitute the bulk of the Lower Palaeozoic rocks in Ireland.

A high thermal gradient down the geofracture would initiate movements of pore waters towards a convective upcurrent. This movement would take advantage of cleavages in the argillites and silts and of porous and permeable sediments. The volume of Lower Palaeozoic rocks contributing metal would be elongate in the Caledonian fold direction and more narrow normal to the axis of folding. A model consistent with these considerations is presented. It assumes uniform leaching in a parallelepiped of vertical thickness 2 km. The top of the source volume lies about 300m below the Old Red Sandstone-Lower Palaeozoic unconformity. The parallelepiped is 15 km long in the direction of the Caledonian axis and 8 km wide.

The vertical axis of this model corresponds to the intersections of the north-south geofractures with the faults of Caledonian trend. The end and side of this figure are thus, respectively 7.5 and 4 km from the intersection at the shortest point. Assuming orders of magnitude for lead, zinc, copper and barium in Table 8-1 the following expressions may be used to calculate the percentage of each element required to form an ore deposit.

$$F = \frac{\text{wt of metal in ore deposit}}{\text{wt of source rock}}$$

Hence F is the proportion of source rock required to form the ore deposit; then the percentage of metal leached from the source volume $= \frac{F}{C} \times 100$, where C = concentration of metal in source rocks. The proportion of the lead required to form the Tynagh ore deposit may be calculated as follows:

Wt of lead in ore deposit = 600,000 tonnes (Table 8-2)

Wt of source rock = 6.55×10^{11} tonnes calculated from a source volume 15 km x 8 km x 2 km with specific gravity of 2.73 (Murphy 1952)

$F = 6 \times 10^5/6.55 \times 10^{11} = 0.92$ ppm

Amount of lead in source rock = 20 ppm (Table 8-1)

Percentage of lead required for ore deposit

$= 0.92/20 \times 100 = 4.6\%$

Estimates of weights of various metals in the ore bodies are presented in Table 8 - 2; they are approximations calculated from published reserves and mined ore and will therefore be underestimates of metal contributed by the upwelling solutions. Assuming the validity of this model, the formation of the Tynagh deposit involves the solution of 4.6 per cent by weight of the total quantity of lead in the source volume, as shown above, 1.8 per cent of the silver, 0.76 per cent of the zinc, 0.17 per cent of the copper and 0.43 per cent of the barium.

Table 8-2. Approximate tonnages of elements in various mineral deposits

Deposit	Pb	Zn	Cu	Ag	Ba
Abbeytown	12,000	26,000	-	-	-
Tynagh	600,000	500,000	50,000	600	2,000,000
Silvermines	500,000	1,000,000	-	500	2,000,000
Gortdrum	-	-	60,000	90	-
Aherlow	-	-	92,500	350	-

The eventual reprecipitation of the metals may have taken place in most cases by reaction with reduced sulphur from Lower Carboniferous residual sea-water (Gillatt 1969; Graham 1970).

The driving mechanism for the hydrothermal systems presents an important problem. Direct magmatic heat comes to mind but must be rejected as there is no spatial relationship between the Lower Carboniferous volcanic centres in the region, and mineralization. Instead a speculative model involving the geofractures themselves is presented below.

Degassing of the mantle resulted in an upward heat transfer and a progressive rise in the geoisotherms (see Bailey 1970), as well as facilitating the formation of the geofractures. The fluids tended to migrate towards the tensile stress concentrations associated with the bottom of the newly formed geofractures (Figure 8 - 7) and see Orowan 1969) which had the effect of focussing heat in those regions. This heat along with that conducted to the fracture walls was then transferred upwards in a convective system in crustal water. The geofractures provided a planar conduit for the upcurrent and nearer the surface the rising plumes took advantage of cross-cutting faults or other permeable structures and eventually mushroomed out. Wherever there was adequate sulphur, base-metals were deposited over the intersections, but where the sulphur was insufficient then smaller deposits were dispersed around the main node. The Castleblayney Veins shown in Figure 9 - 2 may be an example of the latter occurrence.

Recharge of the system took place by relatively cold aqueous solutions permeating down through the upper crust, at the same time leaching metals from authigenic and diagenetic sulphides or adsorbed onto clays in the underlying geosynclinal sediments. Although at depth we would have expected permeability to decrease rapidly due to compaction of voids, effective permeability was still large enough to permit solution migration because of the decrease in the viscosity of water with increasing temperature and the solution of silica from quartz and other minerals (see White 1967a).

Geochemical Considerations

If we assume that the post-Caledonian mineral deposits belong to one metallogenic province then certain variations in the compositions of particular deposits are worthy of study. Copper predominates over lead and zinc in the south of Ireland although there is nearly as much copper at Tynagh as at Gortdrum. Mercury in significant concentrations is restricted to Gortdrum. Zinc-lead ratios are highest at Ballinalack, Moate, Keel and Navan. The latter ore body has a zinc to lead ratio of 5:1; at Abbeytown and Silvermines this ratio is about 2:1 and at Tynagh 0.8:1.

The factors governing the solution of these metals are their availability, and their solubility as complexes. Some of the lead, zinc, copper, silver and mercury may be present in authigenic and diagenetic sulphides, or be associated with clays and organic matter. The ionic radii and electronegativity of lead (Pb^{++}, r=1.20 Å and e = 1.55) and silver (Ag^+, r = 1.26 Å and e=1.42) preclude their incorporation into octahedral or tetrahedral sites in clay mineral structures. Any lead and silver not in the sulphide phase may be adsorbed on the clays and organic matter and is thereby readily available to percolating water. The ionic radius and electronagativity of zinc are the same as those of ferrous ion (r = 0.74 Å and e = 1.66); the zinc is therefore camouflaged by the ferrous ion in clay mineral structures. Barium can substitute for potassium in potash feldspar and is strongly adsorbed into intersheet positions in clay minerals. Fluorine substitutes for OH groups in phyllosilicates.

The high zinc to lead ratios in east central Ireland could be explained by the breakdown of clay minerals releasing the zinc to permeating brines. (The zinc-lead ratio in the underlying geosynclinal rocks is 5:1). The breakdown could have been caused by thermal metamorphism at depth, and a comparison with the Salton Sea thermal waters is interesting in this respect. The temperatures at the bottom of the 1500 m well in the Salton Sea area were reported (Skinner and coworkers 1967) as being between 300°C and 350°C. At this depth the sedimentary rocks are metamorphosed to the low green schist facies. Analyses of reservoir brines from two wells (ibid) gave the significant concentrations in ppm, as lead, 84 and 80; zinc, 790 and 500; barium, 235 and 250; silver, 0.8 and 2; copper, 8 and 3; and fluorine, 15 and not reported. The lower zinc to lead ratios at Tynagh, Abbeytown and Silvermines may then be ascribed to lower temperatures in their respective source regions.

The remaining differences between the ore deposits are best explained in terms of solution chemistry. The outstanding unsolved problem is, if phyllosilicates were destroyed in some regions, why was zinc liberated but not fluorine?

Nriagu and Anderson (1970) have calculated the solubilities of lead, copper, mercuric and cadmium sulphides in concentrated brine solutions. They demonstrated that in sulphur poor brines at low temperatures enough lead (and cadmium), but not mercury and copper can be transported in the form of chloride complexes to account for the formation of ore deposits. This work goes some way towards explaining the differential distribution of metals in the various ore deposits. The zinc-lead deposits in central and northern Ireland may have been derived from chloride rich brines but the low migration capacities of copper and mercury as chloride complexes in sulphur poor brines perhaps suggests a different transporting media in the south. There is no direct evidence on this last point. Hirst (1971) has shown that copper in shales is soluble in dilute acid solutions and Romberger (in Barnes and Czamanske 1967) has demonstrated that covellite is soluble in bisulphide solutions. Mercury could also be transported as a bisulphide complex (ibid) or possibly complexed with the ammonium ion (ibid) and may also be transferred in the vapour phase (White 1967b).

Along with the predominance of copper in mineral deposits in southern Ireland, the Old Red Sandstone is also enriched in that metal. It is not possible to say at this time whether this enrichment is the source of the copper in the south or the escaped remnants from the ore deposits, although, wherever Old Red Sandstone underlies the Carboniferous then the sulphide deposits always contain copper, but where Old Red Sandstone is missing then zinc and lead predominate and the copper content is small or absent.

IX ON THE SIGNIFICANCE OF NEW ORE DISCOVERIES, THE POSSIBLE PRESENCE OF GEOFRACTURES IN SCOTLAND AND THE CORRELATION BETWEEN TECTONIC, MAGMATIC AND METALLOGENIC EVENTS

Introduction

Since the first paper on geofractures was written (Russell 1968), several new facts have emerged against which the geofracture theory may be tested.

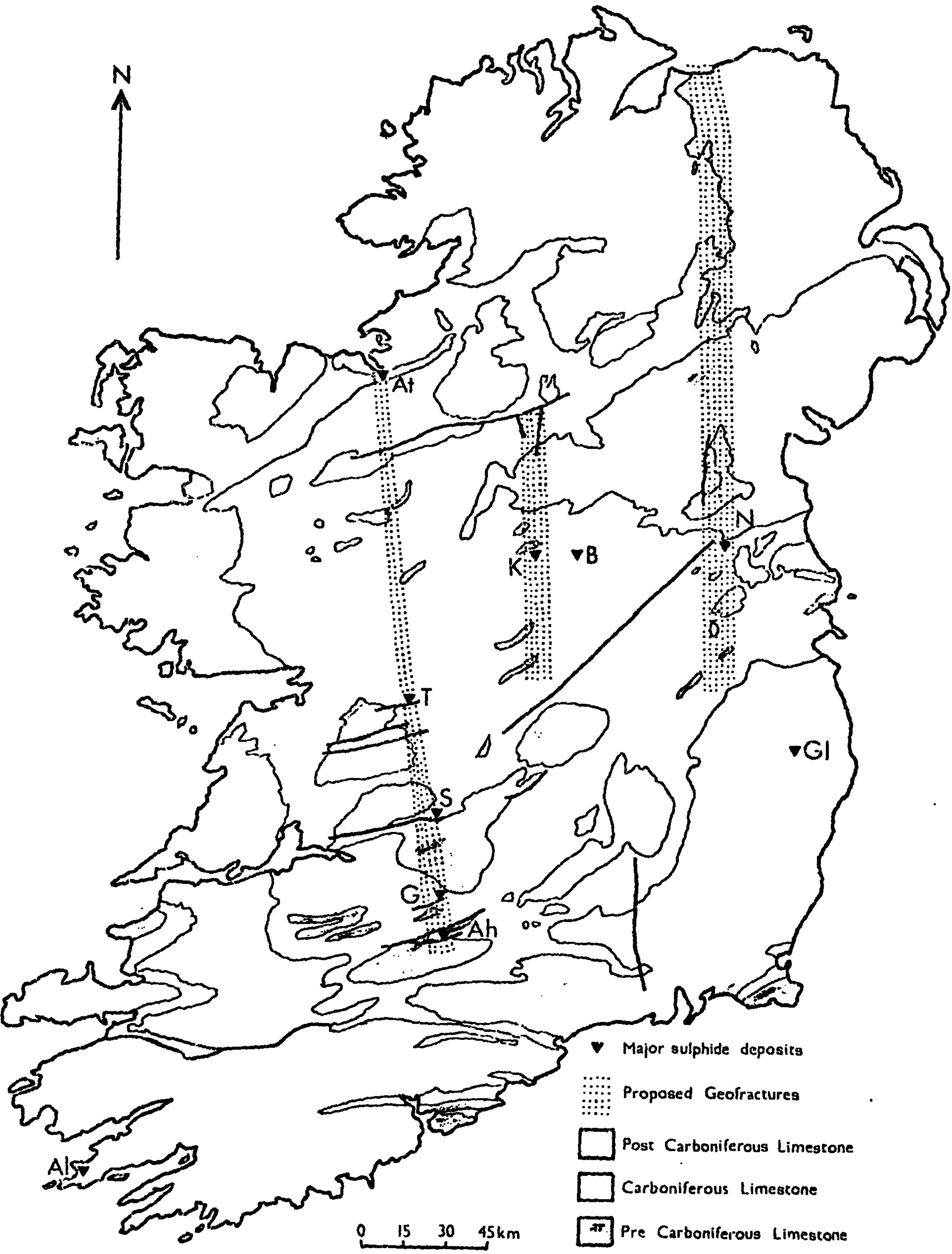
Although the hypothesis outlined in the previous chapter offered a model of devel oping crustal structure consistent with recent theories of the initiation of sea-floor spreading, the evidence available was too limited to test adequately its validity. Whereas the Kingscourt geofracture in eastern Ireland is structurally well defined (Figure 8 - 3), the definition by outcrop of two others (the Abbeytown-Gortdrum and the Keel-Ferbane geofractures) is poor, and the hypothesis rests on relatively few large mineral deposits.

The hypothesis is examined in three ways in this chapter. (1) How do the locations of recent actual ore discoveries compare with predicted locations? (2) Is there evidence for north-south structural controls of mineralization in Scotland, a country which bears the same relation to the continental margin as does Ireland? (3) Does the age of geofracturing fit into the sequence of events leading to the formation of the continental margin west of the British Isles?

New Discoveries

The geofracture hypothesis predicted that hidden base-metal deposits might lie at the intersections of faults of Caledonoid trend with the postulated north-south geofractures (Russell 1968; 1969).

The most important recent discovery has been the large zinc-lead


N
At
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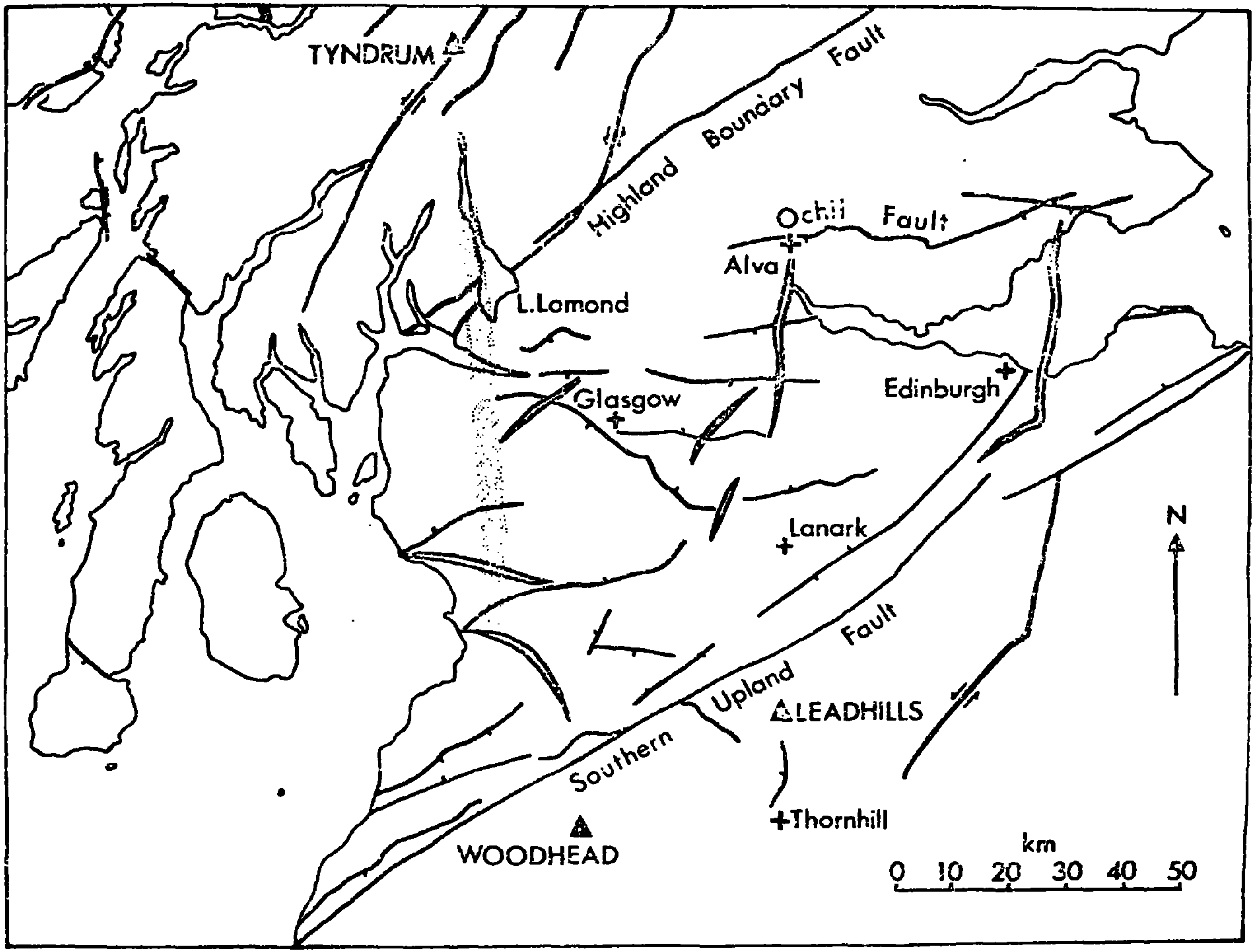
0 15 30 45km
Major sulphide deposits
Proposed Geofractures
Post Carboniferous Limestone
Carboniferous Limestone
Pre Carboniferous Limestone

Figure 9 - 1

Map showing the form and distribution of the postulated north-south geofractures or extension failures in relation to known geology and sulphide deposits containing more than 40,000 tonnes of base-metal. Note that the geofractures are now considered to be zones of structures up to 10 km wide and anomalous in their regional context.

Al	Allihies,	At	Abbeytown,	T	Tynagh,	S	Silvermines,
G	Gortdrum,	A	Aherlow,	K	Keel,	B	Ballinalack,
B	Navan	G	Glendalough				

Ballinalack and Navan are recent discoveries. Geology from Geological Survey of Ireland 1:750,000 geological map 3rd edn. 1962.



FAULTS
SYNCLINES
CRUSTAL INHOMOGENEITY (McLean and Qureshi)
SULPHIDE DEPOSITS
TOWNS

deposit near Navan (O'Brien and Romer 1971). This is situated six kilometres east of the presumed 'surface outcrop' of the Kingscourt geofracture (Russell 1969), on the margins of a positive Caledonian structure. An extensive low grade zinc-lead deposit discovered at Ballinalack (see Schultz 1971) lies 18 km from the nearest geofracture (Figure 9 - 1) and is not known to have Caledonoid structural controls. The metal content of a sulphide deposit discovered in the Vale of Aherlow in 1965 has recently been revealed in a paper by Cameron and Romer (1970) to be nearly 100,000 tonnes of copper and 360 tonnes of silver. It lies in an east-west trending structure of folds and minor faults, 12 km south of Gortdrum, on the southerly extrapolation of the Abbeytown-Gortdrum geofracture (Figure 9 - 1).

Obviously the Ballinalack discovery does not support the hypothesis. The Navan Deposit lying to the south of the Kingscourt outlier (Figure 9 - 3) prompts the suggestion that with the dimensions of the outlier in mind, the structurally higher homologues of this geofracture may be zones of structures up to 10 km wide (Figure 9 - 1).

The Aherlow deposit brings the total number of post-Caledonian ore-bodies that contain, or contained, at least 40,000 tonnes of base-metal up to ten, of which five fall on the Abbeytown-Gortdrum line.

Controls of Post-Caledonian Mineralization in Scotland

Although Scotland lies near to the continental margin and is partly on (Caledonoid) 'strike' with Ireland there are some important geological differences. Both countries have an areal extent of about 80,000 km^2 but Lower Carboniferous rocks in Scotland comprise only 5,600 km^2 of bedrock surface, including some Namurian (see Francis 1965), of which 1,350 km^2 are lavas belonging to an alkali basalt differentiation series (cf Ireland with 37,000 km^2 of Lower Carboniferous). Moreover the Lower Carboniferous succession, which occurs mainly in the Midland Valley, with a lesser area in the extreme south of Scotland (Figure 9 - 2) is dominantly non-marine, and consists of cementstones, mudstones, shales and sandstones. Towards the top of the succession, marine limestones and sandstones, along with a few thin coal seams, occur. Sedimentation was cyclic in inland lakes and later, shallow seas, and kept pace with subsidence; the succession achieves a maximum thickness of 3000 m (ibid). No base-metal deposits of any magnitude have been found in these rocks.

Lead-zinc deposits mainly of vein type do occur in the Caledonian rocks outcropping to the north and south of the Midland Valley, but are generally smaller than their Irish counterparts, perhaps because they lacked the advantage of favourable host rocks.

Several workers have attempted to define belts or lines containing or intersecting most of the mineral deposits in central and south Scotland. MacGregor (1944) pointed out that many of the veins of barytes and other minerals occurred in a belt about 24 km wide aligned approximately northwest-souteast and lying within the Mull dyke swarm. This belt included the Leadhills deposit.

More recently Kutina (1968) has constructed an empirical prospecting net for western Scotland, in which he derived a set of hypothetical northnorthwest faults as a complementary set to the Caledonoid (northeast-southwest) trending wrench faults. Many of the ore localities occur at, or around his intersections.

As in Ireland, there are many small sulphide deposits in Scotland. In Figure 9 - 2 only those three mines in post-Caledonian sulphide deposits on the mainland of Scotland, known to have produced over 5,000 tonnes of high grade ore, are marked (Wilson 1921). The sparse evidence considered by itself is totally inadequate to define a pattern of regional distribution of these deposits. Local concentrations are controlled by faults and joints which trend north-south at Leadhills (MacGregor 1944) and northeast-southwest at Tyndrum. But in each case the single set of fractures does not, by itself, explain a point concentration of ore and the presence of a transverse structure must be postulated.

Major North-south Structures in Scotland

i) The Loch Lomond Crustal Inhomogeneity

McLean and Qureshi (1966) discovered a north-south zone approximately coincident with Loch Lomond in west-central Scotland, across which there is a marked change in the regional gravity field (Figure 9 - 2). They observed that the Dusk Water and Inchgotrick Faults and two Permo-Carboniferous dykes were deflected across the southerly projection of this zone. It is interesting to note here Kutina's suggestion (1968) that a rupture may have been responsible for the elongated form of Loch Lomond and that his hypothetical north-northwest line drawn through the Loch intersects the Tyndrum Fault at the Tyndrum mining district. The northward extrapolation of the 'McLean-Qureshi crustal inhomogeneity' (Figure 9 - 2), however, intersects that Fault in the region of the richest mineralization (see Wilson 1921), so that a more directly north-south control is assumed here.

The demonstrated length of this meridional peculiarity in the crust, considered here to be another example of a geofracture, is about 75 km and it may continue northwards and be responsible for the concentration of ore at Tyndrum.

ii) The Postulated Alva-Thornhill Geofracture

The Leadhills-Wanlockhead vein system was the largest producer of lead and zinc in Scotland (Wilson 1921; MacKay 1959). About half a million tonnes of ore have been removed and the lodes are still not exhausted. In mineral content and dimension, though not in form, this deposit is similar to some of the post-Caledonian base metal bodies recently discovered in Ireland. It is different from the North Pennine ore field in that it contains no fluorite and is not known to have a wide lateral extent.

MacGregor (1944) has pointed out that "the trends of the Leadhills and Wanlockhead veins are parallel to and on the line of faults, with trends a few degrees W. or E. of N., that cut the Permian sandstones and lavas of the Thornhill outlier of Carboniferous rocks a few miles to the south" (Figure 9 - 3). Mykura (1965) has since shown that the 'Permian' sandstones of Thornhill are probably of Upper Carboniferous age. George (1965) considers this outlier to have been a comparatively small syncline in the Southern Upland Massif in Upper Carboniferous times.

The northerly extrapolation of the Thornhill-Leadhills structure approximately coincides with Hall's Lanark Line (Hall 1971) which in turn passes into a north-south syncline that contains the Stirling, Clackmannan and part of the Central Coalfields (Figure 9 - 2 and see Dunning 1966). From isopachyte measurements, Goodlet (1957; 1959) has demonstrated that this was one of several synclines in the Midland Valley of Scotland that were the sites of subsiding troughs during the Carboniferous, at least from upper Viséan (P_2) times.

The axis of this synclinal trough abuts the east-west Ochil Fault at its point of maximum throw (approximately 3 km down to the south (Francis and coworkers 1970). Twenty two kilometres to the west, this fault dies out completely. Francis and coworkers infer that the Ochil Fault has separated a relatively positive area of slow subsidence to the north from a much greater, more continuous subsidence to the south, in Carboniferous times. They also point out that a fault of the same trend may have existed before Upper Old Red Sandstone deposition.

Several veins containing chalcopyrite and barytes, with lesser amounts of galena, erythrite and argentite, occur to the north of the

Fault, notably near to and just to the west and northwest of Alva (Wilson 1921; Geological Survey One-Inch Map of Scotland Sheet 39 (Stirling)).

It is suggested here that the Thornhill syncline is a structurally higher homologue of a geofracture which continues northwards and is occupied by vein minerals at Leadhills. The much larger syncline to the north may be the result of some thinning of a more ductile crust.

The overall length of the postulated Alva-Thornhill geofracture is at least one hundred kilometres.

iii) The Postulated Buckhaven-Innerleithen Geofracture

Two structures; a fault and a syncline, with Caledonoid trends deviate to a northerly direction along a line 45 km east of the postulated Alva-Thornhill geofracture (Dunning 1966) (5 km east of Edinburgh on Figure 9 - 2). Goodlet (1957; 1959) has demonstrated that this syncline too, containing the East Fife and Midlothian coal basins, was in existence in upper Viséan times, and continued subsiding throughout much of the Carboniferous. No major mineralization is known to exist along this structure but its similarity to the Alva-Thornhill structure leads me to consider this to be another example of a geofracture.

Comparison of the Scottish North-south Structures with the Postulated Geofractures in Ireland

The Ochil Fault, which forms the northern boundary of a contemporaneous north-south syncline, resembles structures in Ireland which also control mineralization. One area, that of the Tynagh Mine, shows the Ochil structural pattern on a smaller scale. According to Schultz (1966a) the North Tynagh Fault has a maximum downthrow of about 600 m to the north. The throw lessens to the east and west and may give way partly to increases in the strike slip component. The mineralization is especially concentrated in the region of maximum throw. Moreover, about half a kilometre to the northnorthwest, an east-west

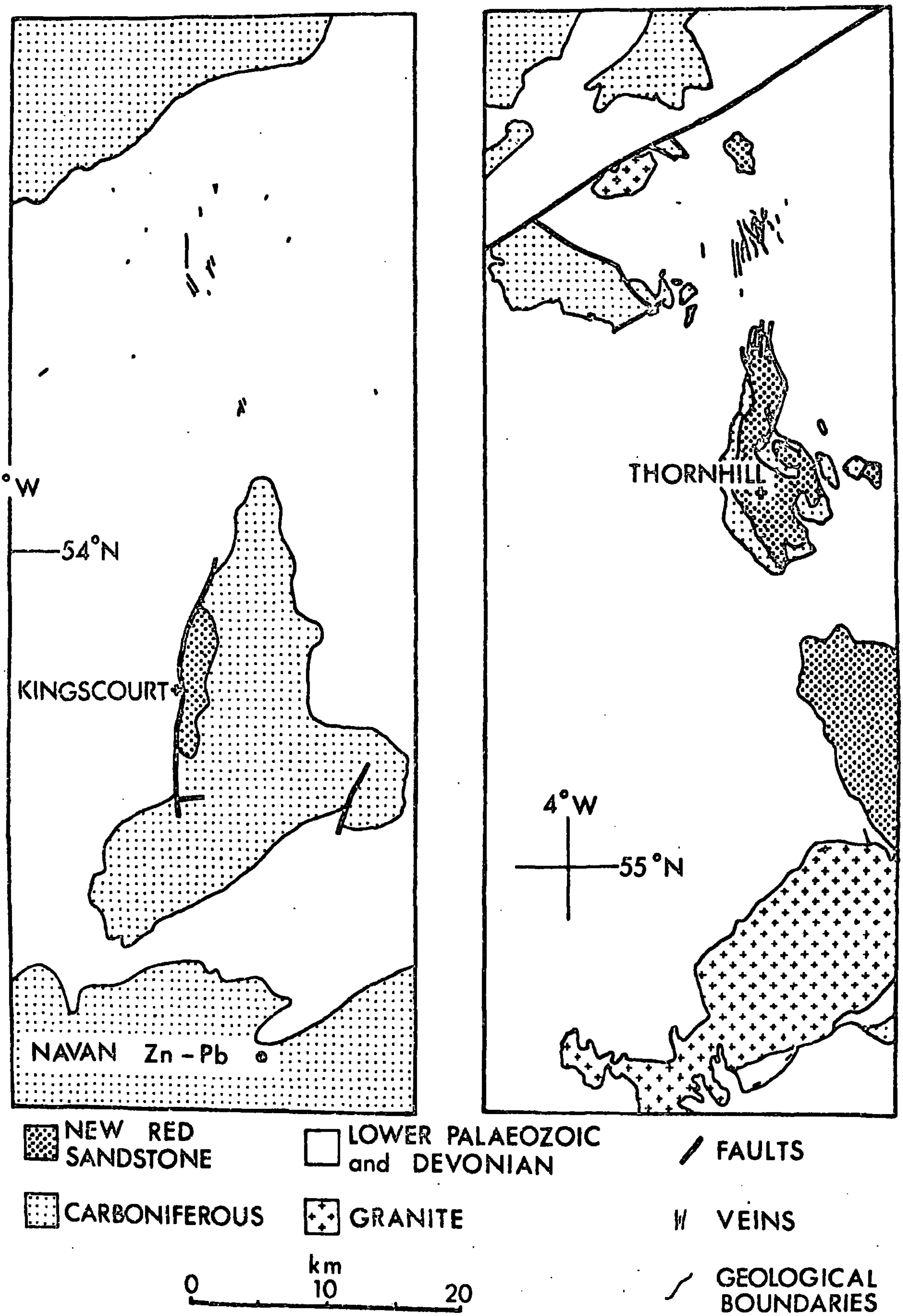

7° W
54° N
KINGSCOURT
NAVAN Zn - Pb
THORNHILL
4° W
55 °N
NEW RED SANDSTONE
CARBONIFEROUS
LOWER PALAEOZOIC and DEVONIAN
GRANITE
FAULTS
VEINS
GEOLOGICAL BOUNDARIES
km
0
10
20

Figure 9 - 3

Comparison of the Kingscourt outlier (Ireland) with the Thornhill outlier (Scotland). The Castleblayney veins occur to the north of the Kingscourt outlier and the Leadhills-Wanlockhead vein system to the north of the Thornhill outlier. Both structures are considered to be components of north-south geofractures. Tara Exploration's new zinc-lead discovery near Navan is also shown. (Geology plotted from the published sheets of the Geological Survey of Ireland One-Inch Map and the Geological Survey One-Inch Map of Scotland).

section (Figure 6 - 1) reveals a thickening of a mid-Dinantian sedimentary iron deposit in the deepest part of a basin. Thus there appears to have been subsidence on the line of the postulated Abbeytown-Gortdrum geofracture in mid-Dinantian times in this region.

The Slievenmuck Fault, trending eastnortheast, also achieves its maximum downthrow (1700 m north according to Mahbub-i-Khuda in Shelford 1963) when crossing the proposed Abbeytown-Gortdrum geofracture 2 km northnorthwest of the copper silver deposit at Aherlow (Figure 5 - 1). In this case, however, nothing is known of the relative thickness of the Carboniferous strata on the downthrow side.

The deflection of structures across the projection of a north-south zone in Scotland (McLean and Qureshi 1966) also has a counterpart in Ireland. To the west of the postulated Abbeytown-Gortdrum geofracture most faults trend between east-west and 10° north of east (Weir 1962; Geological Survey's 'Twelve-Mile' Map of Ireland, Dublin 1962), but to the east the predominant direction is between eastnortheast and northeast (see also Figure 8 - 2).

The Thornhill Basin-Leadhills structure affords us a view of part of a north-south geofracture. It is remarkably similar in outcrop pattern to the Kingscourt outlier and the accompanying Castleblayney veins in eastern Ireland (Figure 9 - 3) which form part of a larger north-south geofracture (Figure 8 - 3).

Discussion and Conclusions

Two of the three Scottish major north-south structures described above include subsiding troughs as component parts. The formation of the troughs is best explained by a stress field in which the direction of relative tension was oriented east-west. The Loch Lomond crustal inhomogeneity does not, in itself, indicate east-west extension but its parallelism with the other structures and with part of the continental margin to the west of Scotland argues for its inclusion into the set of geofractures. The north-south subsiding troughs are located within Caledonoid trending blocks and do not appear to extend to their margins. The Stirling-Clackmannan and the East Fife-Midlothian troughs lie within the Midland Valley of Scotland and the Thornhill and Kingscourt outliers within the Lower Palaeozoic Southern Upland block and its continuation in Ireland. This suggests that within blocks, east-west tension is released by crustal thinning, whereas on their margins it may be dissipated partially by shearing movements along a Caledonoid 'free-surface', such as the Southern Upland Fault.

The Scottish meridional structures described are separated by distances of 45 and 55 km. This is similar to the observed 50 and 65 km spacing of the postulated geofractures in Ireland (Figure 9 - 4). According to present evidence the geofractures in Ireland date from late Tournaisian times. The age of similar structures in Scotland is less easy to determine. They certainly affect upper Viséan sedimentation (Goodlet 1957; 1959), and the Lanark Line (Hall 1971) was in existence in mid-Dinantian times, but information beyond this is lacking.

Although a relationship can be demonstrated between observable north-south structures and two of the larger post-Caledonian sulphide deposits in Scotland, there is no such control of the Woodhead deposit (Figure 9 - 2). Also there are many lodes and veins in Scotland that apparently occur independently of the inferred set of north-south geofractures (see Wilson 1921). So no claim is made that post-Caledonian sulphide mineralization is always dependent on these structures.

The Development of the Northeast Atlantic (Rockall Trough) Margin

Most of the evidence for the development of this margin is provided by rocks and structures in south and central Scotland. After the last phases of the Caledonian orogeny died away at the end of Middle Devonian times there followed a period of tectonic and magmatic quiescence in the British Isles north of Cornubia. The Lower

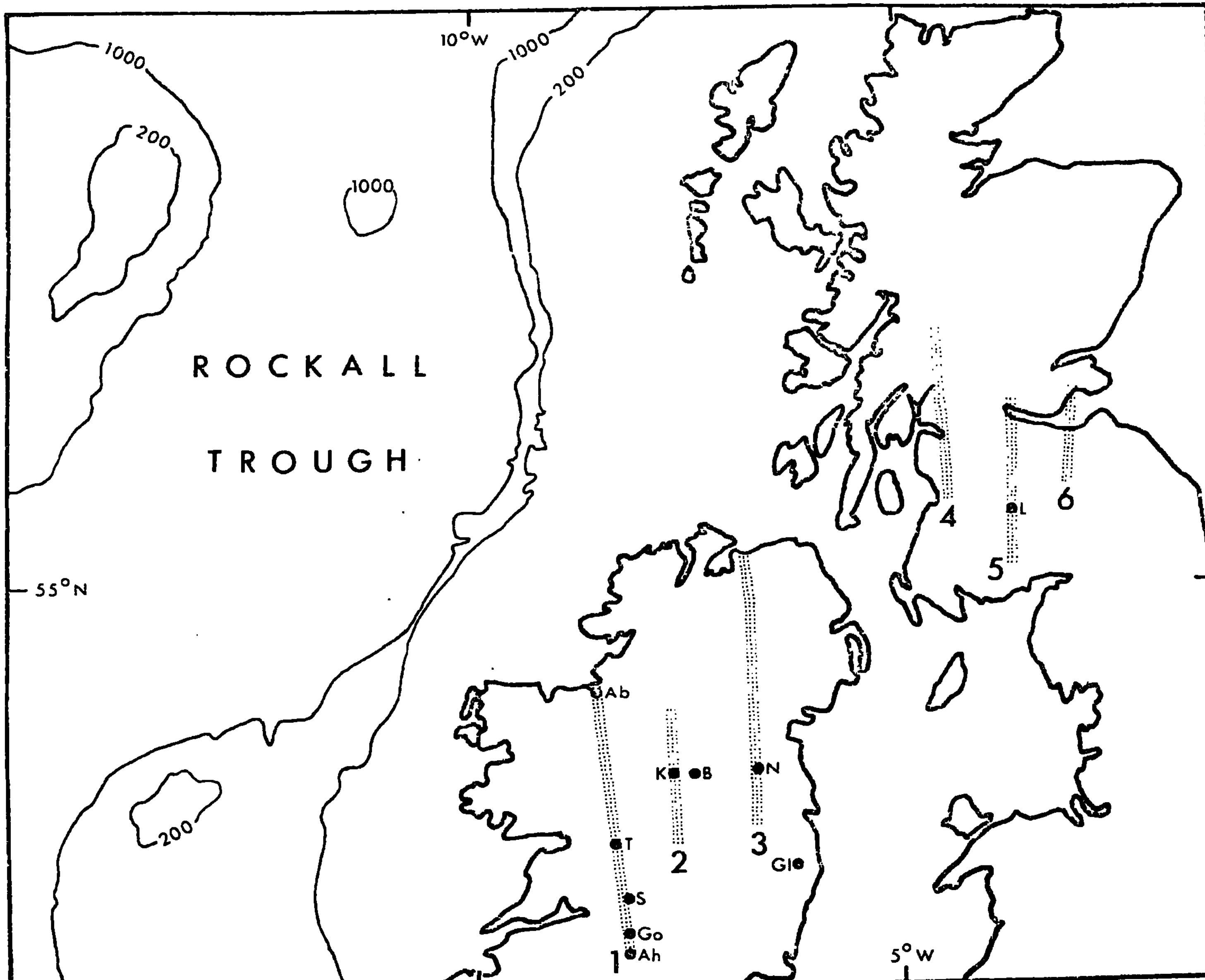
Carboniferous sea spread northwards covering Upper Old Red Sandstone fluvial deposits and reached the Northern Caledonides in the Viséan. But towards the end of the Tournaisian there was a sudden outburst of volcanic activity in the Midland Valley of Scotland and to a lesser extent elsewhere (Francis 1967). The magma type was alkali basalt (Tomkeieff 1937) which may have formed by partial melting of the upper mantle perhaps at depths of 60 km or more (see Kushiro 1965) and rose to the surface by penetrative convection (see Elder 1966).

At about the same time it is thought that the north-south geofractures began to develop in the brittle crust as a response to east-west tensile stresses, though apparently too far above the region of magma generation to exert any control over the distribution of volcanic centres. Two possible reasons for this temporal coincidence present themselves. 1) Partial melting of the upper mantle to form the alkali basalt magma effectively reduced the thickness of the lithosphere and tensile stresses originating elsewhere and transmitted horizontally along the lithosphere (see Elsasser 1969), were thereby focussed in the region under discussion. 2) An ascending column of relatively hot mantle diverged and flowed laterally outwards east and west, tending to drag the lithosphere apart (Oxburgh 1971; McKenzie 1972). This thermal plume rose adiabatically and the displaced mantle material began to melt and alkali basalt magma escaped to the surface. Both possibilities adequately explain the tectonomagmatic data.

Towards the end of the Viséan, volcanic activity became muted and subsiding troughs were being formed in the Midland Valley (Goodlet 1957; 1959). The sea covered much of the Valley and vulcanism was mainly explosive. Sedimentation kept pace with subsidence and the sediment surface stayed around base level until late Westphalian times (Francis 1965), although during the Westphalian itself, mainly nonmarine deltaic conditions prevailed. At about the end of Westphalian times there appears to have been a sudden general uplift at least in northeast Ireland (Charlesworth 1963) and Scotland (Craig 1965). In the southwestern part of the Midland Valley there is a clearly defined lithological break although no angular unconformity exists, between Westphalian and what are now thought to be upper Stephanian rocks of New Red Sandstone aspect (Mykura 1965; 1967; Wagner 1966). The top 300m of Westphalian sediments have been oxidised and Mykura (1967) considers the reddening to be interformational and that a number of non-sequences may be present in these beds. Upper Westphalian sediments in the north-south troughs have also been oxidised down to a maximum depth of 500 m (Francis and Ewing 1962). In Arran and in basins south of the Southern Uplands Fault, New Red Sandstone rests with a strong unconformity on various horizons of the Carboniferous and oversteps on to the Caledonian folded strata (Mykura 1967). In the Thornhill basin volcanic rocks and continental sandstones of probable upper Stephanian age (Mykura 1965) rest with angular disconformity on older Carboniferous rocks (Simpson and Richey 1936).

Just preceding this period of uplift tholeiite magma was intruded into sills and east-west dykes (Fitch, Miller and Williams 1970; Francis 1967) in Central Scotland and northeast England. This type of magma commonly accompanies continental breakup (eg see Gass 1970) but the orientation of the dykes is incompatible with an east-west tensile stress field. A way of resolving this contradiction is to assume that east-west tension had been released by lithosphere separation just before the intrusion.

Geophysical evidence shows that the formation of Rockall Trough preceded the Tertiary opening of the North Atlantic west of Rockall Plateau (Avery, Vogt and Higgs 1969; Roberts 1970; Scrutton 1971). Bott (1971) has suggested that 'Permo-Triassic' basins formed as a result of stresses associated with an unstable young continental margin to the west and Bott and Watts (1970) believe Rockall Trough to have



10°W
1000
200
1000
200
1000
ROCKALL
TROUGH
55°N
200
5°W
1
2
3
4
5
6
Ab
T
S
Go
Ah
K
B
N
Gl
L

Figure 9 - 4

A mercator projection showing the relationship between Rockall Trough and the postulated north-south geofractures in Scotland and Ireland. Bathymetry in metres (Stride and coworkers 1970; Roberts 1970).

Geofractures are numbered as follows -

1 Abbeytown-Gortdrum	2 Keel-Ferbane,	3 Kingscourt,
4 Loch Lomond,	5 Alva-Thornhill,	6 Buckhaven-Innerleithen.

Geofractures 1 - 3 are modified from Russell (1968; 1969).
Post-Caledonian sulphide deposits in Scotland and Ireland with more than 40,000 tonnes of base metal are lettered as follows -

Ab	Abbeytown	T	Tynagh	S	Silvermines	Go	Gortdrum
Ah	Aherlow	K	Keel	B	Ballinalack	N	Navan
Gl	Glendalough	L	Leadhills				

TABLE 9-1 CORRELATION BETWEEN TECTONIC, MAGMATIC AND METALLOGENIC EVENTS IN SCOTLAND AND IRELAND.

TIME MY	SERIES	TECTONICS	MAGMATISM	INFERRED STRESS REGIME	INFERRED REGIONAL TECTONICS	MINERALIZATION
260	LOWER PERMIAN	SUBSIDENCE OF NEW RED SANDSTONE BASINS		STRESSES ASSOCIATED WITH UNSTABLE YOUNG CONTINENTAL MARGIN	OCEAN FLOOR SPREADING IN ROCKALL TROUGH	
270						
280						
290	UPPER CARBONIFEROUS	UPLIFT	MINOR ALKALI BASALT EXTRUSION		LITHOSPHERE SEPARATION AT ROCKALL TROUGH	?
			THOLEIITE INTRUSION	N-S MINIMUM STRESS		
300		SUBSIDENCE OF SYNCLINAL TROUGHS IN MIDLAND VALLEY OF SCOTLAND	INTERMITTENT ALKALI BASALT EXTRUSION AND INTRUSION			
310						
320						
330	LOWER CARBONIFEROUS		MAIN PERIOD OF ALKALI BASALT VOLCANISM	EAST-WEST TENSION		
340						
350		N-S GEOFRACTURING				MINERALIZATION
360						

opened, or been opening at that time. If we place the time of lithosphere splitting at around the Westphalian-Stephanian boundary these events are effectively explained. Regional uplift in the Stephanian may have resulted from the development of anomalously low density mantle beneath the newly formed ocean ridge (see Bott 1971). The cessation of alkali igneous activity by the end of the Carboniferous also fits this model, for the newly forming Trough would have provided a locus for magmatic intrusion and extrusion.

Lithosphere separation may have been by downward propagation of particular north-south geofractures and weakness planes of Caledonoid trend. The spatial relationship between the geofractures and Rockall Trough is shown in Figure 9 - 4. The temporal relationships outlined above (see Table 9 - 1) also support the geofracture concept.

X RELATIONSHIP BETWEEN THE ORE DEPOSITS AND GEOLOGICAL HISTORY

Introduction

Although an appreciation of the total geological environment was important in the formulation of the hypothesis outlined in the two preceding chapters, reference to the Armorican Orogeny was suppressed. Such suppression is normal when formulating a theory; for if all the known facts are given equal weight a current paradigm looks insurmountable not least because interpretations in the literature are grounded in that paradigm. The geofracture theory seemed to me to explain the genesis and siting of mineral deposits in Ireland with less difficulty than recourse to the Armorican Orogeny. Nevertheless the east-west tension theory has its own contradictions and in this chapter I re-examine the geological knowledge pertaining to ore deposition.

Stratigraphical Environment

In chapter II a conventional account of the geological history of Ireland was presented. Figures 2-1 and 2-2 show the distribution of ore deposits in relation to the Dinantian transgression. Spatially, the ore deposits are clearly situated independently of the sedimentary environment. Ore deposits occur in Carboniferous and pre-Carboniferous rocks; this is even the case within individual deposits such as Silvermines and Keel. It is true that there is evidence for mineralization related to a particular sedimentary environment at Tynagh and at Silvermines, but this is an aspect of deposition rather than of source and siting. Also, at Allihies copper was deposited in cross cutting veins that postdate the Armorican folding (Sheridan 1964) and so these veins are Permian or younger.

We can say then that major mineralization took place over a period beginning in late Tournaisian times and continued at least in one case, into the Permian, and that stratigraphy is important only in the deposition of ore.

Therefore we have to look elsewhere to explain the source of the constituents, the mechanism that drove the mineralizing fluids and governed where the fluids escaped near or at the surface. The geofracture theory does explain the distribution of the deposits but not the variations in metallic ratios nor the age of at least one of the deposits.

The Armorican Orogeny

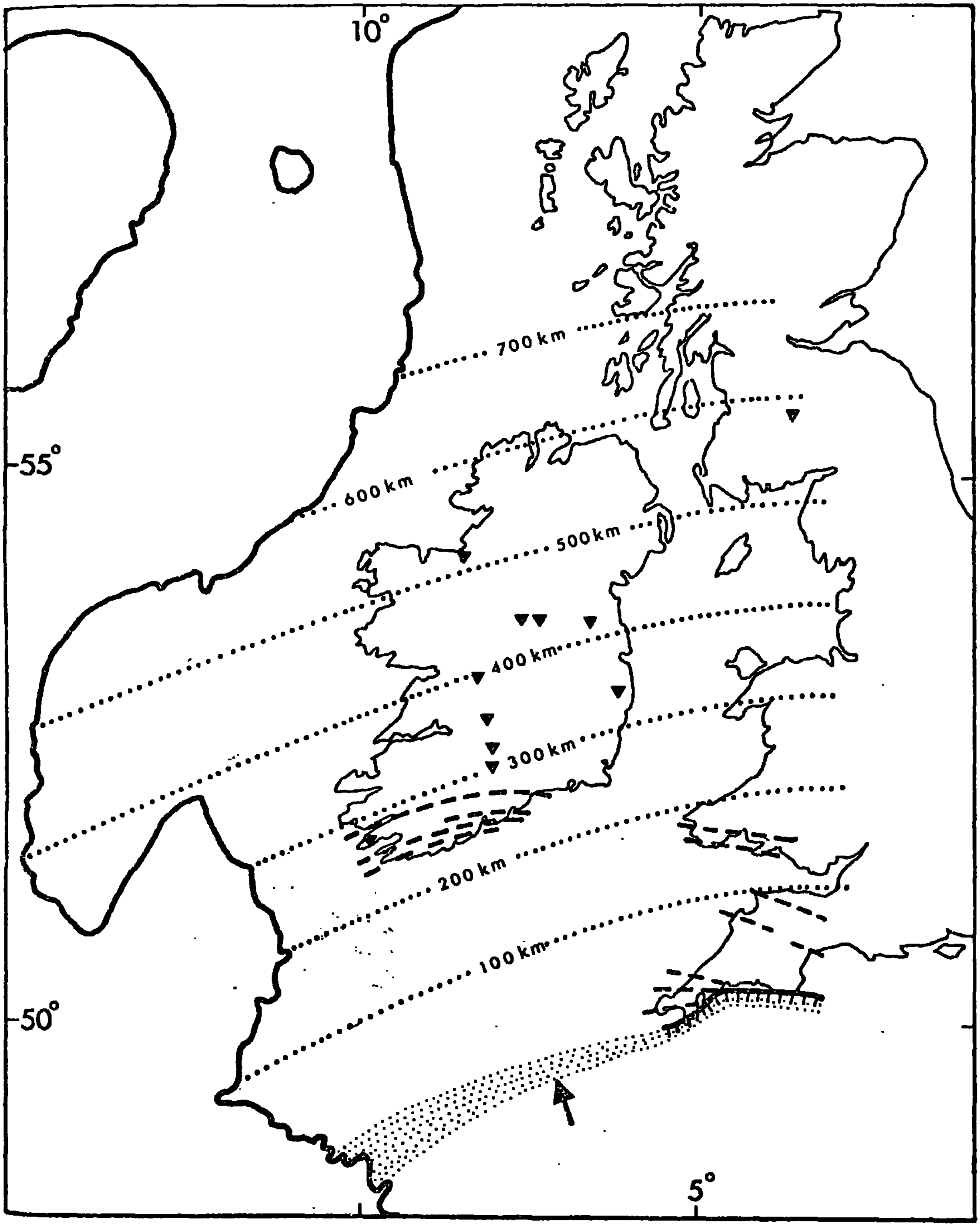
There are several reasons why the Armorican Orogeny was not uppermost in my mind when considering the origin of the mineralization. One of these was due to a personal blind spot; I was unfamiliar with the inner zone of the orogenic belt. Also the Pennine blocks (near Durham) were normally considered to be Hercynian features; an assignment that was unconvincing and not calculated to instil a respect for that Orogeny. Added to this was the fact that all the major east-west faults associated with ore deposits in Carboniferous rocks were obviously of normal type, requiring explanation in terms of at least local north-south relative tension. This finding was in sharp contrast to that expected from Gill's work published in 1962 before most of the evidence from the ore deposits became available (see Figure 2 - 3).

If an orogeny were to be taken seriously then the least to be expected was the transmission of compressive stress through the crust over a reasonable distance. Moreover, there were no Armorican granite batholiths outcropping in southern Ireland, and such igneous activity as there was in the Carboniferous had more in common with the Midland Valley of Scotland to the northeast than with that in Cornwall.

The climax of the Armorican Orogeny, however, took place at the end of the Carboniferous as evidenced by granitic intrusions and thrusts in Devon and Cornwall and steep folds and some thrusts in southern Ireland. At the same time I have proposed that only a short distance to the northwest and north, ocean floor spreading began after 60 my of tensile strain caused by east-west tension. The two theories, therefore, appear to be in opposition.

Obviously, the 'east-west relative tension' theory is not without its internal contradictions and certain aspects of the Armorican Orogeny cannot be explained away.

An important new dimension to the argument is introduced if the Armorican Orogeny is considered in terms of plate tectonics. Building especially on a paper by Isacks and coworkers (1968), Dewey and Bird (1970) have shown that a variety of phenomena in orogenic belts may be explained in terms of plate theory. These phenomena interrelate in such a way that a history of a geosyncline and its subsequent orogeny can be unravelled. Hutton's principle that'the past history of our globe must be explained by what can be seen to be happening now' is used, and Dewey and Bird isolated various components that give the clue to earlier plate motions. Briefly, ophiolites (a sequence of ultra basic rocks, gabbro, dyke complexes, pillow lava and chert) are thought to represent oceanic mantle and crust, and therefore mark the site of ancient trenches and subduction zones. The subduction zone is the region where an ocean plate slides into the asthenosphere. Seismic activity at the top of the slab (the Benioff zone) allows us to trace the path of the slab of lithosphere, and it generally dips at an angle of 45^{o}. Wedges of relatively light sediment are too bouyant to be carried down at the same time and are scraped off against the facing plate causing some folding. Any sediments trapped in cracks in the lithosphere formed on original bending are soon melted on being transported into the relatively hot regions below surface and the consequential magma rises to form intrusive and extrusive igneous rocks and high temperature/pressure metamorphism. A Benioff zone therefore usually underlies an island arc or mountain belt adjacent to a continent. 'Frictional' heating at greater depth gives rise to



10°
55°
50°
5°
700 km
600 km
500 km
400 km
300 km
200 km
100 km

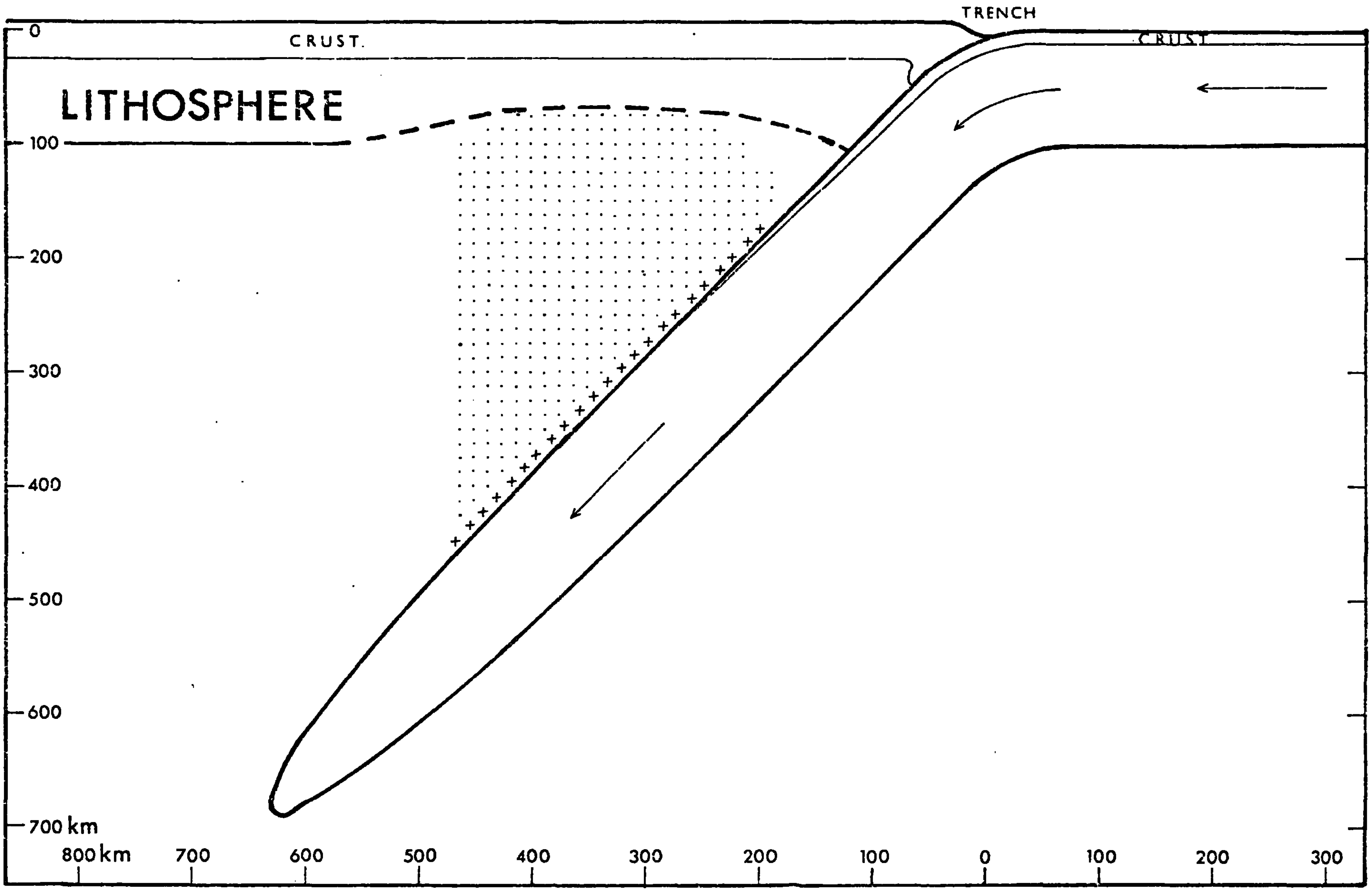
Figure 10 - 1

Mercator projection of the British Isles and the 1000 m bathymetric contour. Broken lines: Armorican structural trends. Ticked line: Armorican thrust. Stippling: metamorphic basement (Day and coworkers 1956) considered here to represent the Armorican subduction zone. Arrow on plate being consumed shows relative movement. Dotted lines: depth contours to top surface of consumed slab of lithosphere assuming an angle of 45° dip of the Benioff zone. Red triangles: post-Caledonian deposits mentioned in text.

igneous activity at some distance from the trench. When two continents collide in such a manner then deformation is more extreme and plate motion is finally halted in that region.

Although Zwart (1969) considers the Hercynian Orogeny merely to represent a region of high heat flow, it is possible, at least for part of the orogenic belt, to make a reconstruction in terms of plate tectonics. The ophiolite zone is represented by the Lizard Series which consists of serpentine, gabbro, dolerite and epidiorite as well as schists and gneisses; schists also outcrop at Dodman Point and Start Point to the northeast and east respectively. Day and coworkers (1956) have outlined the westsouthwesterly continuation of this 'metamorphic basement' on geophysical evidence (Figure 10 - 1). This zone is considered here to be where a plate moving north was consumed into the upper mantle, according to volcanic evidence, probably from Middle Devonian times onwards. The northerly direction is supported by igneous activity and metamorphism in Cornwall and Devon north of the ophiolite belt. The fact that the ophiolites are older than the volcanic activity and deformation in Cornwall (Green 1966) is to be expected as the ocean crust, which the ophiolites are assumed to represent, was in existence before it reached the subduction zone (eg see Mitchell and Reading 1971). If we assume that the plate slipped down northwards at an angle of 45° until it reached the mantle at about 700 km depth then the submerged slab would underlie the entire British Isles excepting north Scotland (Figure 10 - 1). According to present earthquake evidence however (Isacks and coworkers 1968), the overall dips of Benioff zones may vary from at least 30° to 70° so it is impossible to calculate the actual depth of the downgoing slab at particular points in Ireland.

Inserting these possibilities into the known geology of Ireland, folding and thrusting in the south may be explained conventionally by transmission of compressive stress northwards generated by the collision of continental Europe with the British Isles. Earlier east-west normal



TRENCH
CRUST.
CRUST
LITHOSPHERE
0
100
200
300
400
500
600
700 km
800 km
700
600
500
400
300
200
100
0
100
200
300

Figure 10 - 2

Diagram showing possible thermal effects of a descending slab of lithosphere. Crosses: region of 'frictional' heating. Dotted zone: occurrence of partial melting. (After Hasebe and coworkers 1970). Note that the elevation of the isotherms above the zone of 'frictional' heating causes the thinning of the lithosphere. Concommitant high heat content in the crust may be dissipated by convective transfer in formation waters.

faulting and basin formation to the north could be due to extension related to magma diapirs or intercrystalline melt rising from the Benioff zone and solidifying in cooler areas near the surface (eg see Elsasser 1970). Some of the magma could have reached the surface as alkali basalt or its differentiates and the high heat flow could have aided mineralization as the heat was dissipated by driving convective systems of pore waters. The elevation of geotherms above the descending plate would also have caused thinning of the lithosphere so that stresses originating elsewhere could have been concentrated in the region of the British Isles (Figure 10-2).

It is therefore possible to resolve the contradictions in both the east-west tension theory and the Armorican Orogeny by a synthesis of the two.

Synthesis

From Middle Devonian times to the beginning of the Permian a northerly dipping slab of lithosphere was consumed at the southern edge of Cornwall down a Benioff zone or series of Benioff zones that underlay most of the British Isles. 'Frictional' heat generated along the zone of shearing rose mainly by mass transfer causing thinning of the overlying lithosphere, elevating the heat flow, and effecting some minor extension of the crust. An east-west tensional stress field originating elsewhere was 'focussed' in this region of thin lithosphere causing north-south geofracturing towards the end of the Tournaisian. These geofractures allowed heat to escape by convection in pore waters. The heat flow, however, would have remained high over a period of time, perhaps of the order of over 100 my (Hasebe and coworkers 1970); so mineralization likewise could have spanned such a period, that is from late Tournaisian to the Permian.

A possible example of the interaction of the two geological events; that is east-west tension and a descending lithosphere, is found in the south of Ireland. Dawson-Grove (1955) has shown that there were three, nearly contemporaneous, phases of deformation in County Waterford. North-south compression gave east-west folds; an east-west relative tension gave north-south normal faults; and a shearing stress produced wrench faults trending east-west with a dextral shift. Also, in Kerry important wrench faults with a dextral shift which approximately parallel the strike, were formed contemporaneously with or only slightly later than the folding (Capewell 1957). If we assume that these are all first order structures then this region marks the transition in Hercynian times between a compressive stress regime to the south and the east-west tensional stress field acting in Ireland throughout most of the Carboniferous. The east-west dextral shears may then be considered as the complex surface manifestation of a minor transform fault or faults along which the northern plate slides to the east away from the incipient opening of a trough to the west of Ireland and Scotland.

It must be emphasized that the components of this unified synthesis may be interdependent. For example, it is possible that without the high heat flow and the consequent thinning and plasticity of the lithosphere, the strain effects of east-west tension would not have occurred over such a large area. Without the Armorican Orogeny east-west stresses might have been released by a discreet rifting similar in style to the Rhine Graben. Mineralization likewise would have been much more restricted.

XI CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

Contrary to expectation the reconnaissance trace element studies reported on here exclude syngenesis and local lateral secretion as a possible origin for the Tynagh, Gortdrum, Oola, Carrickittle and Ballyvergin base-metal sulphide deposits. The findings on Tynagh and Gortdrum are in agreement with Morrissey, Davis and Steed (1971). Likewise the Ballyvergin results endorse the epigenetic model proposed by Hallof, Schultz and Bell (1962) for that deposit. Apart from the Silvermines upper 'G' orebody which on present knowledge appears to be syngenetic there is a concensus of opinion in favour of an epigenetic explanation for the remainder of the base-metal deposits occupying Lower Carboniferous rocks in Ireland. Indeed temperatures of up to 365^{o}C for the deposition of sulphides are probable (Greig and coworkers 1971) implying that the mineralizing solutions must have risen from depths well below the Carboniferous rocks. In fact sulphides are present in Lower Palaeozoic rocks at Keel and in the Silvermines area and it is inferred here that the Leadhills deposit in Scotland, occurring solely in Lower Palaeozoics, resulted from a similar process to the Irish mineralization.

One of the outstanding problems of ore genesis in Ireland is the age or ages of ore deposition. Without this knowledge it is not possible to relate ore genesis to a particular tectonic event with confidence. My own predisposition is for a mid-Dinantian age, at least for the onset of the mineralization. This view is based on the chemical support found in this thesis for an 'exhalative' origin for the Tynagh chert-hematite deposit first mooted by Derry, Clark and Gillatt (1965), and the syngenetic aspect of the Silvermines upper 'G' orebody (Weber 1964; Graham 1970). By analogy the Keel iron oxide deposit may have a similar origin to Tynagh. Continuing in this way of thinking the chert deposit at Silvermines could have originated from spent hydrothermal solutions escaping to the surface after deposition of the 'G' orebody, bringing me to a final speculation that the chert at Aherlow may have had a similar origin. These ideas could be tested by an investigation of the spatial relationship between the sulphide bodies and the chert and/or iron oxide deposits, as well as by a chemical investigation of the Keel iron deposit. There is evidence of fault movements having taken place in mid-Dinantian times in some mineralized areas, namely Silvermines (Graham 1970), Tynagh (Morrissey and coworkers 1971), Gortdrum (Thompson 1967) and Keel (Patterson 1972). Nevertheless most of the vertical movement must have post-dated Lower Carboniferous sedimentation so where the Carboniferous is faulted against older rocks the roots of any mid-Dinantian mineralization may be revealed (eg Silvermines and Keel).

A mid-Dinantian age for the onset of mineralization allows ore genesis to be related to the Armorican Orogeny and the local structural controls also support such a relationship. The major structural controls postulated in this thesis on the other hand favour a correlation with continental breakup. With two of the three newly announced sulphide deposits of significant size lying broadly on the postulated north-south geofractures the case for continuing research into north-south controls appears good. One method first suggested by Watson Laing (1969) is satellite imagery. The synoptic view of the country provided by such imagery may reveal settlement over deep seated structures. The theory should also be used as an exploration guide. Five significant discoveries of base-metal sulphides were made between 1961 and 1965 but only two have been found since then. Clearly ore is becoming harder to find. It may lie hidden beneath bogs or be related to faults along which there has been little subsequent movement and hence no exposure. Murphy (1962a) has shown that such faults may be revealed by detailed gravity survey. Where faults (actual or inferred) cross the postulated geofractures and soil geochemistry is unlikely to reveal ore because of peat cover or depth of burial, it will be necessary to drill for information. A pattern of shallow drilling should provide an approximation of the local structure and subsequent deeper drilling may hopefully intersect a base-metal deposit or perhaps a pointer to ore in the form of trace element aureoles.

From this preliminary survey two main types of aureole are suggested. The Ballyvergin-Gortdrum type consists of a halo of arsenic and lead around copper deposits in Lower Limestone Shales and Muddy Limestone (mercury is also significant at Gortdrum). The Tynagh-Carrickittle type consists of erratic values of lead, zinc, barium, arsenic, mercury and, more important, a widespread envelope of manganese surrounding lead, zinc, (copper) deposits in the Waulsortian limestone. The extensive manganese enrichment in the Waulsortian near Tynagh lends itself to a more intense study, for this limestone is unusual in that it is chemically homogeneous, unweathered, non-porous and apart from large joints, impermeable.

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APPENDIX I

XRF OPERATING CONDITIONS AND ANALYTICAL ERROR

OPERATING CONDITIONS FOR TRACE ELEMENT DETERMINATIONS BY X-RAY FLUORESCENCE SPECTROMETRY

Element	Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	W
Line	L_β	K_α	K_α	K_α	K_α	K_α	K_α	K_β	K_α	L_ℓ
Tube	W	W	W	W	W	W	W	W	W	W
Peak$^\circ$ 2θ	40.7	60.9	65.9	71.6	15.9	35.6	37.8	43.6	32.6	72.5
Low background	39.7	59.7	65.1	70.6	-	34.5	36.8	42.0	-	-
High background	41.5	-	66.8	-	17.9	36.8	38.8	-	-	73.5
Generator KV	48	48	48	48	54	48	48	48	48	48
Ma	20	20	20	20	16	20	20	20	20	20
Crystal	LiF110	LiF110	LiF110	LiF110	LiF110	LiF110	LiF110	LiF110	LiF	LiF110
Path	Vac	Vac	Vac	Vac	Vac	Vac	Vac	Vac	Air	Vac
pump down time secs	60	60	60	60	60	60	60	60	-	60
Collimator μ	480	480	480	480	480	480	480	480	480	480
Counter	Scint.	Scint.	Scint.	Scint.	Scint.	Scint.	Scint.	Scint.	Gas flow	Scint.
Counter voltage	980	980	980	980	860	980	980	980	980	980
Fixed time secs.	60	60	60	60	60	60	60	60	30	60
Holder	Rotating circular aluminium with mylar window									
Sample state	Powder	Powder	Powder	Powder	Powder	Powder	Powder	Pellet	Pellet	Powder

ACCURACY, PRECISION AND DETECTION LIMITS OF THE

Argillaceous limestones:	NBS No 1A. This study. Thompson et al (1970). Experimental precision on ten replicate determinations of sample 19 (mean and standard deviation). Detection limits.
Igneous rocks:	USGS G1. This study. Fleischer (1965) 'best values'. USGS W1. This study. Fleischer (1965) 'best values'. Detection limits.
Shales:	Detection limits.
Sandstones:	Detection limits.
Ironstones:	Experimental precision on ten replicate determinations of sample 655 (mean and standard deviation). Detection limits.

TRACE ELEMENT ANALYSES (PARTS PER MILLION)

Pb	Zn	Cu	Ni	Ba	Sr	Rb	Mn	As
21	27	23	16	252	1967	22	240	<25
15±2	28±4	14±3	12±3	124±6	2000±117	18±5	341±48	-
20±6	40±2	10±4	28±4	233±10	463±8	18±3	1580±13	35±10
17	6	8	8	16	5	5	30	25
51	52	17	<5	350	259	208	198	
49	45	13	1-2	1220	250	220	230	
<15	82	124	91	<16	166	21		
8	82	110	78	180	180	22		
15	5	5	5	16	5	5	10	
17	6	8	8	19				
15	5	7	7	16				

Pb	Zn	Cu	Ni	Ba
2400±15	140±5	35±3	145±9	9000±6
40	13	20	20	20

ACCURACY, PRECISION AND DETECTION LIMIT OF THE MERCURY ANALYSES (PARTS PER BILLION)

			Hg
USGS	sample 1	This study	47
		USGS	42
		Koksoy et al (1967)	70
USGS	sample 2	This study	184
		USGS	150
		Koksoy et al (1967)	190

Experimental precision on ten replicate determinations of sample 800 (mean and standard deviation)	25 ± 15
Detection limit	20

APPENDIX 2

BACKGROUND STUDIES

(Bracketed samples were collected from the same bed, but separated by short strike distance) Pb, Zn, Cu, Ni, Ba, Sr, Rb, As, Mn and Mo are recorded in parts per million, Hg as parts per billion and S, SiO_2, Al_2O_3, $CaCO_3$ and Fe_2O_3 in percent.

Rush Section	Zone	Succession	Sp no.	Classification
(Smyth, 1915, 1951; Hudson, Clarke and Sevastopulo 1966) (Area 5)	D_2	Posidonomya Limestone	{ 27	Limestone
			26	"
			{ 25	Limestone
			24	"
	D_1	Dolomite	{ 31	Dolomite
			30	($MgCO_3$~36%)
			{ 29	Dolomite
			28	"
	C_2S_1 (S_2?)	Kate Rocks	{ 23	Limestone
			22	"
			21	"
			20	"
	C_2S_1	Carlyan Limestone	19	Limestone
			{ 18	"
			15	"
			14	"
			{ 17	Limestone
			16	"
			{ 13	Shaly limestone
			12	"
	C_2S_1	Supra Conglomerate Limestone	{ 11	Limestone
			10	"
	C_2S_1	Rush Conglomerate	9b	Limestone shale
			9a	Limestone
			8a	Shaly limestone
			8b	Limestone shale

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	29	30	37	306	2618	17	-	-	93	-	-	-	-	-
~17	15	33	23	276	3328	<5	<25	98	-	0.57	24.4	1.9	70.1	1.5
~17	15	18	34	-	-	-	-	-	-	-	-	-	-	-
<17	14	21	26	260	973	9	-	-	35	-	-	-	-	-
<17	<6	51	28	204	38	<5	-	-	-	-	-	-	-	-
<17	<6	18	21	160	-	-	<25	5950	23	0.07	2.9	0.0	52.3	6.0
<17	<6	9	<8	-	-	-	-	-	-	-	-	-	-	-
<17	<6	21	14	204	46	9	-	-	-	-	-	-	-	-
<17	<6	<8	<8	-	-	-	-	-	-	-	-	-	-	-
~17	10	<8	12	206	280	<5	-	-	-	-	-	-	-	-
<17	<6	<8	<8	-	302	<5	<25	2154	28	0.20	5.1	0.20	89.6	1.0
<17	9	12	9	214	277	<5	-	-	-	-	-	-	-	-
20	40	10	28	233	463	18	-	2032	-	0.26	11.3	2.4	80.4	1.7
29	36	29	49	346	271	65	-	-	85	-	-	-	-	-
34	76	45	72	-	-	-	-	-	150	-	-	-	-	-
<17	113	24	46	346	266	69	-	-	-	-	-	-	-	-
<17	36	12	21	-	382	33	<25	5250	-	0.38	14.1	1.7	69.5	3.9
~17	43	16	26	244	362	19	-	-	-	-	-	-	-	-
21	79	23	33	-	-	-	-	-	-	-	-	-	-	-
20	237	28	54	320	290	57	-	-	60	-	-	-	-	-
30	21	12	20	-	-	-	-	-	-	-	-	-	-	-
23	11	11	22	266	377	14	-	-	-	-	-	-	-	-
47	282	48	86	1670	254	115	-	-	106	-	-	-	-	-
28	122	23	30	3176	449	37	-	-	-	-	-	-	-	-
32	440	27	56	1650	404	45	35	1418	-	0.22	31.6	7.0	48.1	5.6
50	198	50	110	1804	245	190	52	602	-	0.15	48.7	14.4	16.2	7.3

Zone	Succession	Sp no.	Classification
C_2S_1	Rush Slates	7	Limestone
C_1		6	Limestone
		5	"
Z_2,		3	Limestone
		2	"
		1	Limestone

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
23	60	28	38	280	1091	23	<25	403	-	0.13	15.9	3.3	74.1	2.4
<17	55	18	33	252	993	20	-	-	33	-	-	-	-	-
39	22	22	40	-	-	-	-	-	-	-	-	-	-	-
21	17	14	50	278	1114	36	-	-	42	-	-	-	-	-
<17	13	26	42	350	936	13	<25	891	-	0.26	19.6	3.8	69.5	2.6
<17	18	19	28	250	1218	10	-	-	57	-	-	-	-	-

	Zone	Succession	Sp no.	Classification
Ardmore Bay section (Area 14) Smyth 1939)	C	Waulsortian	109	Waulsortian limestone
		Bank Complex	108	
			107	"
			106	"
			105	Waulsortian limestone
			104	Waulsortian limestone
			103	Waulsortian limestone
			102	Waulsortian limestone
			101	Waulsortian limestone
	C	Shale	98	Silt
	C	Black Lime-	100	Limestone
		stone	99	"
Hook Head section (Area 14) (Smyth 1930, George 1960)	C_1	Chonetes Beds	50	Limestone
			49	"
	C_1	Linoproductus	53	Limestone
		Beds	54	"
			51	Limestone
			52	Limestone
			66	Limestone
			65	"
	C_1	Supra Dolomite	64	Limestone
			63	"
			62	Limestone
			61	"
	C_1	Dolomite	60	Dolomite
			59	(Mg(0$_3$ ~ 36.5%)
			58	Dolomite
			57	(Mg(0$_3$ ~ 37%)
	Z_2	Michelina	56	Limestone
		Favosa Beds	55	"
			68	Limestone
			67	"

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	11	<8	<8	-	-	-	-	-	21	-	-	-	-	-
21	7	<8	9	-	-	-	-	-	43	-	-	-	-	-
<17	<6	9	11	186	180	<5	<25	<30	-	0.00	0.9	0.5	96.0	0.2
<17	<6	~8	14	-	-	-	-	-	-	-	-	-	-	-
<17	<6	<8	<8	192	190	<5	<25	<30	-	0.03	0.7	0.4	97.0	0.2
<17	~6	11	10	196	203	<5	-	-	23	-	-	-	-	-
<17	<6	<8	9	-	-	-	-	-	-	-	-	-	-	-
<17	~6	16	9	194	225	<5	28	-	46	0.01	0.7	0.3	97.7	0.1
19	27	14	29	226	207	9	-	-	-	-	-	-	-	-
24	245	33	200	530	65	208	-	1509	-	0.02	66.4	14.0	0.0	3.7
~17	37	17	25	-	-	-	-	-	49	-	-	-	-	-
19	25	<8	21	180	449	15	-	-	41	-	-	-	-	-
<17	99	~8	10	234	539	16	<25	43	37	0.15	18.9	0.9	78.4	0.5
20	38	12	<8	-	-	-	-	-	-	-	-	-	-	-
<17	9	15	24	250	806	16	<25	<30	-	0.26	21.3	3.5	69.3	1.9
<17	<6	15	<8	224	383	<5	-	-	-	-	-	-	-	-
<17	<6	<8	19	-	-	-	-	-	-	-	-	-	-	-
<17	<6	18	12	220	376	8	-	-	~20	-	-	-	-	-
<17	33	~8	19	-	-	-	-	-	-	-	-	-	-	-
27	85	<8	12	250	361	14	-	-	35	-	-	-	-	-
29	84	11	28	276	284	9	33	82	-	0.18	16.2	3.7	71.5	1.6
30	108	15	28	-	-	-	-	-	-	-	-	-	-	-
<17	<6	<8	~8	196	270	8	-	-	25	-	-	-	-	-
<17	<6	<8	9	-	-	-	-	-	-	-	-	-	-	-
20	<6	<8	17	170	54	20	34	150	-	0.08	7.5	1.5	52.6	1.2
31	<6	15	19	-	-	-	-	-	-	-	-	-	-	-
<17	79	<8	<8	-	58	11	<25	265	23	0.05	2.2	0.3	51.5	0.4
<17	57	<8	12	216	41	7	-	-	-	-	-	-	-	-
29	47	<8	<8	-	-	-	-	-	-	-	-	-	-	-
31	73	<8	<8	200	223	<5	-	-	29	-	-	-	-	-
19	96	14	16	-	-	-	-	-	-	-	-	-	-	-
18	40	14	9	210	442	<5	-	-	-	-	-	-	-	-

Zone	Succession	Sp no.	Classification
Z_1	Michelina	70	Limestone
	Favosa Beds	69	"
		72	Limestone
		71	Limestone shale
K_2	Fish Shales	74	Limestone shale
		73	" "
		75	Shaly limestone
		76	" "
		78	Limestone shale
		77	Shaly limestone
K_1	Grey Sandstone and Transition Group	79	Shale
		81	Red Sandstone
		80	"
		85	Grey Sandstone
		92a	Grey Sandstone
		92b	"
		82	Red Sandstone
		84	"
		83	Shale
	Old Red Sandstone	41	Green shale
		42	Red sandstone
		43	Red sandstone
		44	Red shale
		45	Conglomerate
		91	Conglomerate
		90	Red shale
		89	Red shale
		48a	White sandstone
		48b	"

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	16	~8	<8	-	-	-	-	-	-	-	-	-	-	-
<17	16	14	<8	236	355	6	<25	265	48	0.11	4.5	0.8	89.2	1.1
<17	6	10	17	238	513	10	-	-	40	-	-	-	-	-
<17	52	16	86	440	164	180	26	217	-	0.02	52.8	16.8	12.7	6.2
<17	53	20	65	405	169	154	-	-	-	-	-	-	-	-
24	56	17	68	466	177	154	36	683	-	0.16	53.6	15.4	14.0	6.0
<17	27	11	23	-	-	-	-	-	48	-	-	-	-	-
20	16	12	30	364	145	45	<25	2307	-	0.23	29.4	4.9	44.6	6.6
40	55	16	75	515	128	188	-	-	-	-	-	-	-	-
<17	15	15	27	-	-	-	-	-	29	-	-	-	-	-
<17	40	26	70	535	121	222	84	361	-	0.15	60.5	19.8	3.8	3.9
165	123	35	35	372	-	-	-	-	-	-	-	-	-	-
<15	58	92	41	254	-	-	-	-	-	-	-	-	-	-
<15	15	10	13	-	-	-	-	-	-	-	-	-	-	-
102	1570	22	12	438	65	37	-	-	133	-	-	-	-	-
52	235	12	11	-	-	-	-	-	57	-	-	-	-	-
<15	<5	<7	<7	195	-	-	-	-	-	-	-	-	-	-
<15	9	42	<7	215	-	-	-	-	-	-	-	-	-	-
26	30	45	75	340	79	184	138	<30	-	0.50	65.8	20.2	0.0	3.8
<17	53	9	65	525	-	-	-	-	-	-	-	-	-	-
<15	12	18	9	430	-	-	-	-	-	-	-	-	-	-
<15	~5	<7	<7	446	-	-	-	-	-	-	-	-	-	-
<17	43	16	69	606	-	-	-	-	-	-	-	-	-	-
<15	<5	74	<7	214	-	-	-	-	-	-	-	-	-	-
<15	9	12	26	290	-	-	-	-	-	-	-	-	-	-
<17	19	117	31	340	-	-	-	-	-	-	-	-	-	-
<17	32	16	55	360	-	-	-	-	-	-	-	-	-	-
<15	6	652	<7	195	-	-	-	-	-	-	-	-	-	-
<15	18	135	29	293	-	-	-	-	-	-	-	-	-	-

Zone	Succession	Sp no.	Classification
		88	Red sandstone
		87	Red conglomerate
		86	Red shale
		47	Red shale
		46	Red sandstone

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
21	36	24	65	405	-	-	-	-	-	-	-	-	-	-
<15	10	13	12	234	-	-	-	-	-	-	-	-	-	-
21	44	18	73	460	-	-	-	-	-	-	-	-	-	-
<17	44	~8	62	430	-	-	-	-	-	-	-	-	-	-
<15	22	<7	22	312	-	-	-	-	-	-	-	-	-	-

	Zone	Succession	Sp no.	Classification
Castleisland-Tralee (Area 13)	Z_2	Springmount Limestone	112	Limestone
			111	"
			110	Limestone
	KZ_1	Lower Limestone Shale	113	Shale
		Old Red Sandstone	115	Red sandstone
			114	"

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_3	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	<6	10	<8	–	–	–	–	–	–	—	–	–	–	–
<17	17	9	<8	198	345	<5	28	<30	–	0.02	5.6	0.5	91.5	0.3
<17	<6	10	12	150	215	13	–	–	–	—	–	–	–	–
20	115	33	84	468	–	–	–	–	–	—	–	–	–	–
<15	46	10	90	485	–	–	–	–	–	—	–	–	–	–
<15	48	11	42	405	–	–	–	–	–	—	–	–	–	–

Palleskenry Foynes Section (Area 9) (Shephard-Thorn 1963)	Zone	Succession	Sp no.	Classification
	C_1	Waulsortian Bank Complex	186	Waulsortian limestone
			185	"
			184	"
			216	"
			215	"
			230	"
			229	"
	Z_2	Ballysteen Limestones	228	Limestone
			227	"
			226	Limestone
			225	"
			224	"
			223	"
			222	"
			221	"
			220	Limestone
			219	"
			218	"
			214	Limestone
	Z_1	Lower Limestone Shales	213	Shaly Limestone
			212	Limestone
			211	Shaly limestone
			210	Limestone
			209	Limestone shale
			208	" "
			207	Limestone
			206	"
			205	Limestone shale
			204	" "

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Mo	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	<6	12	<8	-	-	-	-	-	-	~20	-	-	-	-	-
<17	<6	12	<8	-	-	-	-	-	-	-	-	-	-	-	-
20	<6	14	~8	174	49	<5	-	-	-	-	-	-	-	-	-
<17	<6	<8	<8	-	-	-	-	-	-	<20	-	-	-	-	-
<17	<6	<8	<8	182	161	<5	-	-	-	26	-	-	-	-	-
<17	<6	11	<8	206	163	<5	-	-	-	<20	-	-	-	-	-
~17	<6	10	19	-	-	-	-	-	-	39	-	-	-	-	-
18	18	21	34	-	-	-	-	-	-	-	-	-	-	-	-
<17	14	18	26	216	955	13	-	-	-	-	-	-	-	-	-
<17	66	11	26	-	-	-	-	-	-	-	-	-	-	-	-
28	21	10	<8	-	-	-	-	-	-	45	-	-	-	-	-
23	133	15	16	262	514	23	-	-	-	-	-	-	-	-	-
<17	90	~8	<8	-	-	-	-	-	-	-	-	-	-	-	-
20	73	11	10	-	-	-	26	124	-	-	0.13	4.1	1.2	88.8	2.4
<17	49	<8	10	220	482	6	-	-	-	57	-	-	-	-	-
<17	17	17	23	-	-	-	-	-	-	-	-	-	-	-	-
20	79	22	16	160	1764	<5	31	74	-	-	0.08	27.5	1.8	66.5	1.2
18	7	23	20	244	1333	19	-	-	-	65	-	-	-	-	-
~17	10	15	14	236	1042	19	-	-	-	62	-	-	-	-	-
23	24	13	23	276	967	49	-	-	-	56	-	-	-	-	-
<17	94	11	14	222	913	<5	-	-	-	-	-	-	-	-	-
<17	~6	16	63	336	767	92	43	664	<2	-	0.23	40.3	8.7	40.6	4.6
25	63	18	39	160	417	<5	44	880	~2	-	0.46	17.4	2.9	70.3	4.5
~17	46	47	83	564	150	270	35	272	<2	-	0.05	58.8	19.3	5.8	5.8
<17	47	43	82	566	81	260	<25	298	-	45	0.02	64.2	19.3	0.0	5.7
20	31	15	12	210	1042	<5	35	1739	<2	34	0.22	6.7	1.4	80.7	6.0
19	23	15	19	244	737	<5	-	-	<2	-	-	-	-	-	-
30	73	22	46	-	-	-	-	-	~2	-	-	-	-	-	-
17	75	23	49	370	594	134	33	496	~2	-	0.02	39.6	10.8	36.4	4.6

Zone	Succession	Sp no	Classification
		202	Limestone shale
		201	" "
		199	Limestone
		196	Shaly limestone
		195	" "
K	Lower Limestone Shales	198	Limestone shale
		197	" "
		194	Shaly limestone
		191	Limestone shale
		193	Shaly limestone
		192	Limestone shale
Km		139	Shaly limestone
		138	Shale
		140	Sandstone
		137	Limestone shale
		136	" "
	Old Red Sandstone	189	Sandstone
		188	"
		135	"
		134	"
		131	Shale
		133	Sandstone
		130	Shale

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Mo	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
44	447	21	70	350	374	107	29	1072	~2	295	0.13	32.7	8.3	48.0	5.0
41	321	30	77	360	351	105	-	-	<2	198	-	-	-	-	-
26	~6	12	24	248	586	7	27	1589	<2	214	0.30	9.8	1.5	80.1	3.2
47	96	21	35	-	-	-	-	-	<2	150	-	-	-	-	-
<17	107	26	33	380	846	96	<25	973	<2	-	0.16	26.7	6.3	59.0	2.8
<17	53	11	77	830	252	242	~25	318	~2	-	0.08	53.6	15.7	12.5	7.1
<17	53	20	77	602	239	229	-	-	4	-	-	-	-	-	-
46	93	29	37	348	927	64	<25	1126	<2	-	0.15	19.3	4.9	69.2	2.7
<17	40	<8	69	584	273	249	<25	493	<2	-	0.09	50.1	15.8	16.4	6.0
<17	37	11	37	464	202	70	<25	470	<2	53	0.05	56.1	9.0	21.0	5.7
<17	33	66	41	530	243	164	<25	583	<2	-	0.11	50.7	12.8	19.4	5.9
42	100	~8	39	510	436	67	-	-	-	-	-	-	-	-	-
57	45	59	116	880	57	302	167	274	~2	-	0.03	64.6	19.6	0.0	5.0
<15	36	21	62	663	-	-	-	-	<2	-	-	-	-	-	-
36	115	32	43	860	670	107	65	717	~2	-	0.05	40.7	10.5	34.0	7.1
~17	89	14	35	630	535	115	-	-	-	-	-	-	-	-	-
<15	22	16	29	3358	-	-	-	-	<2	-	-	-	-	-	-
<15	<6	32	~8	3180	-	-	-	-	<2	-	-	-	-	-	-
<15	~6	<8	<8	175	-	-	-	-	-	-	-	-	-	-	-
<15	<6	9	<8	181	-	-	-	-	-	-	-	-	-	-	-
21	24	935	117	1144	2700	283	-	-	-	-	-	-	-	-	-
<15	9	<8	18	390	-	-	-	-	-	-	-	-	-	-	-
<15	16	12	94	770	-	-	-	-	-	-	-	-	-	-	-

	Zone	Succession	Sp no.	Classification
Kilmore section	S_1	Calp	183	Limestone
(Area 9a)			182	"
			181	"
	C_1	Waulsortian Bank Complex	180	Waulsortian limestone
			179	" "
			177	" "
			176	" "
			178	" "
	KZ	Lower Limestone Shales	173	Silt
			172	"
			175	Silt
			174	"
			168	Shale
			167	"
			166	"
			165	"
			164	Limestone
			163	"
			170	Limestone
			169	"
			145	Siltstone
			147	Sandstone
			146a	"
			146b	"
		Old Red Sandstone	143	Red sandstone
			142	" "
			148	" "
			149	" "
			150	Green silt
			152	Sandstone
			151	"

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Mo	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	10	30	15	300	684	<5	<25	264	2	37	0.08	41.7	0.9	51.6	0.6
23	69	195	75	-	-	-	-	-	-	-	-	-	-	-	-
<17	45	27	30	150	196	<5	-	-	-	-	-	-	-	-	-
<17	~6	10	<8	-	-	-	-	-	-	33	-	-	-	-	-
18	<6	10	<8	-	-	-	-	-	-	-	-	-	-	-	
<17	<6	<8	<8	-	-	-	-	-	-	85	-	-	-	-	
20	6	12	<8	156	195	<5	<25	<30	-	-	0.02	0.0	0.2	99.2	0.0
<17	<6	<8	<8	-	-	-	-	-	-	-	-	-	-	-	-
<15	136	213	94	644	-	-	-	-	-	-	-	-	-	-	-
64	324	154	146	507	43	127	304	2952	-	-	0.02	68.5	14.2	0.0	9.6
<15	153	62	99	800	-	-	-	-	-	-	-	-	-	-	-
<15	200	89	93	781	-	-	-	-	-	-	-	-	-	-	-
32	85	35	62	950	58	145	37	1683	-	-	0.03	71.3	13.7	0.4	4.9
40	102	27	65	520	53	129	34	2039	-	-	0.02	68.2	14.1	0.0	5.7
30	162	21	52	605	68	145	<25	600	-	-	0.06	66.2	16.2	2.2	4.0
17	360	36	52	526	65	161	-	-	-	-	0.01	72.3	13.4	0.3	4.5
30	33	14	15	-	-	-	-	-	-	-	-	-	-	-	-
19	8	~8	<8	244	514	8	-	-	-	-	-	-	-	-	-
<17	13	<8	<8	204	464	<5	-	-	-	-	-	-	-	-	-
21	<6	12	<8	-	-	-	-	-	-	-	-	-	-	-	-
503	196	9	393	-	-	-	-	-	~2	-	-	-	-	-	-
<15	57	91	54	683	-	-	-	-	<2	-	-	-	-	-	-
270	94	<8	28	468	-	-	-	-	~2	-	-	-	-	-	-
<15	84	92	68	586	-	-	-	-	-	-	-	-	-	-	-
735	44	20	10	385	-	-	-	-	-	-	-	-	-	-	-
235	136	14	15	405	-	-	-	-	-	-	-	-	-	-	-
<15	59	<8	60	996	-	-	-	-	-	-	-	-	-	-	-
<15	45	13	46	386	-	-	-	-	4-	-	-	-	-	-	-
<15	101	340	110	1090	-	-	-	-	~2-	-	-	-	-	-	-
<15	89	70	82	332	-	-	-	-	-	-	-	-	-	-	-
<15	76	23	64	410	-	-	-	-	-	-	-	-	-	-	-

Zone	Succession	Sp no.	Classification
		154	Sandstone
		153	"
		156	"
		155	"
		158	"
		157	"
		160	"
		159	"
		161	"

Pb	Zu	Cu	Ni	Ba	Sr	Rb	As	Mn	Mo	Hg	SiO_2	Al_3O_3	$CaCO_3$	Fe_2O_3
<15	73	12	100	351	-	-	-	-	-	58	-	-	-	-
<15	81	10	128	390	-	-	-	-	<2	-	-	-	-	-
20	27	<8	37	293	-	-	-	-	-	-	-	-	-	-
<15	42	<8	74	390	-	-	-	-	-	-	-	-	-	-
<15	54	<8	55	488	-	-	-	-	-	-	-	-	-	-
<15	77	16	62	507	-	-	-	-	-	-	-	-	-	-
<15	23	92	16	390	-	-	-	-	-	-	-	-	-	-
<15	27	18	20	370	-	-	-	-	-	52	-	-	-	-
<15	49	<8	79	527	-	-	-	-	-	-	-	-	-	-

APPENDIX 3

AUREOLE STUDIES

Ballyvergin Individual analyses of argillaceous limestones. Classification as in Hallof and coworkers (1962), see Figures 4 - 3 and 4 - 4.

Drill hole and sample number		Classification	Depth m
BV22	1	SH-LST	69.5
	2	"	70.7
	3	"	73.0
	4	"	73.2
	5	"	75.9
	6	"	88.5
BV21	1	"	64.2
	2	"	68.3
	3	"	68.6
	4	"	70.7
	5	"	75.6
	6	"	76.8
BV20	1	"	65.8
	2	"	68.0
	4	"	73.2
	5	"	74.1
	6	"	76.2
	3	"	77.8
BV13	4	L_1LST	39.7
	M1	SH-LST	57.1
	M2	"	63.4
	1	"	67.1
	2	"	67.8
	3	"	71.7
	5	MXRK	79.4
BV12	M1	SH-LST	38.4
	M2	"	50.3
BV4	M1	"	57.4
	M2	"	58.9

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Mo	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	87	<8	90	694	76	244	114	171	<2	0.07	58.5	20.2	0.0	8.7
<17	69	24	92	716	76	249	86	134	<2	0.12	59.9	20.4	0.0	7.4
25	68	18	61	688	264	230	65	597	7	0.44	47.0	17.0	20.6	5.4
23	75	33	55	550	406	167	77	1216	<2	0.44	39.1	14.2	32.6	5.4
77	85	17	40	434	514	46	90	2832	4	0.40	16.2	5.2	70.4	4.3
22	110	26	77	622	272	212	65	2213	<2	0.43	24.9	7.7	57.6	5.0
149	125	15	77	496	341	138	309	928	5	0.24	43.8	11.3	30.9	5.4
96	66	<8	52	434	433	90	885	2742	~2	0.29	31.6	8.0	50.1	4.4
76	75	11	70	516	360	136	83	952	<2	0.34	42.9	11.9	31.5	5.4
44	81	9	90	630	175	224	522	535	<2	0.21	54.1	17.4	11.3	6.3
33	78	11	83	644	130	197	70	548	<2	0.27	55.6	16.9	9.8	6.5
1640	63	92	43	374	162	59	10200	2750	<2	0.25	47.5	8.5	34.0	3.8
77	68	30	64	634	361	186	1030	685	8	0.35	41.9	14.7	28.4	5.7
212	65	11	66	620	220	212	365	509	<2	0.30	50.8	16.2	16.5	6.5
96	68	466	71	474	402	118	406	2166	4	0.36	35.4	10.4	41.6	5.6
232	69	37	57	430	416	100	900	3112	<2	0.36	30.5	8.6	51.0	4.4
261	368	888	55	476	431	122	68	737	~2	0.29	40.1	12.4	34.2	6.0
68	110	28	75	536	304	166	172	697	<2	0.28	48.4	14.4	22.2	5.9
34	39	3700	58	600	315	113	27	1728	11	0.45	35.2	11.0	42.0	4.6
700	57	5100	58	980	446	188	96	973	7	0.72	41.1	14.1	29.7	6.4
427	51	5250	35	830	296	201	159	889	12	0.51	46.2	13.6	25.4	6.2
376	82	1036	80	626	173	224	145	574	<2	0.26	53.8	16.9	12.8	5.8
337	87	518	51	494	346	139	560	995	<2	0.29	44.6	13.2	28.4	5.5
367	88	15	41	390	572	78	1450	994	<2	0.35	31.3	8.8	48.6	5.0
530	56	22	66	456	153	108	566	2322	<2	0.26	45.1	10.5	33.7	3.8
30	120	14000	10	850	397	114	29	1728	47	0.99	33.6	11.0	42.8	5.5
188	51	6750	70	846	281	138	77	1103	7	0.47	48.0	14.0	25.0	4.6
231	68	6200	57	1800	425	194	41	899	31	0.34	47.2	13.0	27.7	4.0
350	76	8000	75	1070	119	268	30	757	15	0.29	57.1	18.0	9.4	5.6

Drill hole and sample number		Classification	Depth m
BV7	1	L_1LST	67.1
	2	SH-LST	80.9
	4	"	82.6
	3	"	86.6
	5	"	96.0
BV10	M1	"	76.8
	M2	"	81.1
BV11	M1	"	56.4
	M2	"	59.5
BV18	1	"	62.7
	4	"	71.3
	6	"	71.6
	2	"	72.5
	3	"	74.4
	5	"	76.0
BV19	6	"	67.2
	1	"	68.6
	2	"	70.8
	3	"	71.9
	4	"	73.9
	5	"	75.6

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Mo	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
4020	375	444	40	444	316	98	105	1068	<2	0.56	30.6	8.0	52.3	3.8
415	85	<8	57	500	383	147	115	1125	<2	0.37	41.6	11.5	33.2	5.8
222	83	16	72	438	274	187	97	768	3	0.27	47.3	14.9	21.7	6.2
771	150	<8	49	436	366	96	1140	1762	~2	0.31	37.7	9.8	39.3	5.3
~17	66	592	65	542	217	153	<25	2178	<2	0.12	38.2	11.8	37.1	4.3
555	43	900	75	370	532	63	44	3740	6	0.43	28.1	7.1	54.1	4.4
85	40	5800	25	500	137	60	54	3118	6	0.40	46.3	8.0	36.4	3.3
375	40	6500	22	1850	220	228	71	827	20	0.49	51.3	14.5	20.1	5.3
85	47	10000	80	730	309	174	67	1072	23	0.66	46.1	13.0	27.4	5.6
77	65	11	75	516	329	168	45	613	<2	0.24	44.9	13.3	27.1	5.7
26	65	18	89	650	148	224	70	394	7	0.30	55.8	17.6	9.2	6.3
35	187	30	75	554	265	182	83	604	<2	0.29	47.5	15.0	21.2	6.9
<17	56	<8	77	650	145	256	42	256	<2	0.16	57.9	18.6	6.2	5.7
51	230	17	62	504	391	131	119	2610	<2	0.32	37.0	10.5	40.7	4.3
~17	65	26	98	658	140	251	271	494	<2	0.24	56.3	18.6	8.4	5.3
48	107	<8	72	464	509	99	137	1578	<2	0.80	27.6	8.9	51.9	6.3
<17	51	11	69	536	496	140	<25	775	<2	0.34	34.6	11.1	42.4	4.7
28	52	26	65	774	367	216	62	625	<2	0.42	44.7	17.4	23.1	5.4
58	72	33	93	630	270	210	98	416	<2	0.39	48.3	16.0	19.3	6.6
34	55	22	101	620	226	205	86	312	<2	0.25	56.0	15.9	13.4	5.7
337	69	11	76	558	270	191	90	480	<2	0.30	49.2	14.0	21.4	6.3

BALLYVERGIN Summary of trace element contents of argillaceous limestone in each drill hole and at Pallaskenry

		Pb	Zn	Cu	Ni	Ba	Sr	Rb	Mn	Mo	As	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
Pallaskenry	n	9	9	9	9	7	7	7	6	7	6	6	6	6	6	6
(weathered)	R	<17- 47	~6-447	16- 47	33-83	336- 566	81-767	92-270	272-1072	<2- 2	<25- 43	0.02-0.23	27-64	6.3-19.3	0-59	2.8-6.0
195, 196, 201, 202, 204, 205, 208, 209, 211	M	~25	135	28	60	418	452	152	629	~2	~27	0.10				4.8
Pallaskenry	n	6	6	6	6	6	6	6	3	3	3	3	3	3	3	3
(unweathered)	R	<17- 26	~6-94	11- 18	12-39	160-276	417-1042	5-49	880-1739	<2-2	27-44	0.22-0.46	7-17	1.4-2.9	70-81	3.3-6.0
199, 206, 207 210, 212, 213	M	20	40	14	22	227	777	11	1403	~2	35	0.33				4.6
BV 22	n	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	R	<17-77	68-110	<8- 33	40-92	434-716	76-514	46-249	134-2832	<2-7	65-114	0.07-0.44	16-60	5.2-20.4	0-70	4.3-8-7
	M	~27	82	20	69	617	268	191	1194	~2	82	0.31				6.0
BV 21	n	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	R	33-1640	63-125	<8-92	43-90	374- 644	130- 433	59-224	535-2750	<2-5	70-10200	0.21-0.34	32-56	8.0-17.4	10-50	3.8-6.5
	M	340	81	24	69	516	267	141	1409	<2	2012	0.27				5.3
BV 20	n	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	R	63-261	65-368	11-888	55-75	430-634	220-431	100-212	509-3112	<2-8	68-1030	0.28-0.36	31-51	8.6-16.2	17-51	4.4-6.5
	M	158	125	243	65	529	356	151	1318	~3	474	0.32				5.7
BV 13	n	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	R	337-700	51-88	15-5250	35-80	390-980	173- 572	78-224	574-995	<2-12	96-1450	0.26-0.72	31-54	8.8-16.9	13-49	5.0-6.4
	M	441	73	2384	53	664	367	116	885	~4	482	0.43				5.8
BV 12	n	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	R	30-188	51-120	6750-14000	10-70	846-850	281-397	114-138	1103-1728	7-47	29-77	0.47-0.99	34-48	11.0-14.0	25-43	4.6-5.5
	M	109	86	10375	40	848	339	126	1415	27	53	0.73				5.1
BV 4	n	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	R	231-350	68-76	6200-8000	57-75	1070-1800	119-425	194-268	757-899	15-31	30-41	0.29-0.34	47-57	13.0-18.0	9-28	4.0-5.6
	M	291	72	7100	66	1435	272	231	828	23	36	0.32				4.8
BV 7	n	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	R	~17-771	66-150	<8-592	49-72	436-542	217-383	96-187	768-2178	<2-3	<25-1140	0.12-0.37	38-47	9.8-14.9	22-39	4.3-6.2
	M	356	96	154	61	479	310	146	1458	<2	341	0.27				5.4

		Pb	Zn	Cu	Ni	Ba	Sr	Rb	Mn	Mo	As	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
BV 10	n	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	R	85-555	40-43	900-5800	25-75	370-500	137-532	60-63	3118-3740	6	44-54	0.40-0.43	28-46	7.1-8.0	36-54	3.3-4.4
	M	320	42	3350	50	435	335	62	3429	6	49	0.42				3.8
BV 11	n	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	R	85-375	40-47	6500-10000	22-80	730-1850	220-309	174-228	827-1072	20-23	67-71	0.49-0.66	46-51	13.0-14.5	20-27	5.3-5.6
	M	230	44	8250	51	1290	265	201	950	22	69	0.58				5.5
BV 18	n	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	R	<17-77	56-230	<8-30	62-98	504-658	140-391	131-256	256-2610	<2-7	42-271	0.16-0.32	37-58	10.5-18.6	6-41	4.3-6.9
	M	~36	111	18	78	583	236	202	1211	≤2	105	0.26				5.7
BV 19	n	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	R	<17-337	51-107	<8-33	65-101	464-774	226-509	99-216	312-1578	<2	<25-137	0.25-0.80	28-56	8.9-17.4	13-52	4.7-6.6
	M	86	68	18	79	597	356	177	697	<2	80	0.42				5.82

Limerick Volcanics

	Sp no.	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	S	Pb	Zn	Cu	Ni	Ba	Sr	Rb
Upper Limerick Volcanics	125	42.3	12.8	14.1	13.1	11.7	2.1	0.7	3.04	0.21	0.16	<15	110	68	307	1900	1010	<5
	ULV	47.8	12.9	13.9	10.8	8.9	2.2	0.3	3.06	0.21	0.16	<15	177	74	140	2900	827	<5
Lower Limerick Volcanics					$MgCO_3$	$CaCO_3$												
Herbertstown Weathered Tuff	124	35.4	10.5	10.8	26.4	13.1	0.6	0.8	2.23	0.17	0.15	<15	90	80	87	3000	1064	<5
Quirkes Quarry	123	35.5	10.4	11.3	13.9	23.2	1.9	1.6	2.04	0.17	0.19	18	95	35	543	990	446	60
" "	122	43.9	15.6	11.0	11.4	10.1	3.3	1.8	2.64	0.25	0.08	<15	117	40	145	1225	1403	27
" "	121	35.2	12.9	11.4	23.1	11.8	1.6	1.6	2.15	0.22	0.21	<15	135	37	60	2100	612	33
" "	120	37.8	14.0	11.4	17.6	13.0	0.9	2.9	2.23	0.18	0.09	<15	123	31	167	4800	1403	39
					Mg O	Ca O												
Caherconlish Sill	119	61.5	18.2	5.5	2.2	0.4	3.7	7.7	0.74	0.09	0.00	17	74	7	11	1770	396	121
" "	118	60.9	18.4	5.8	1.8	1.7	4.8	6.0	0.71	0.09	0.00	<15	109	11	11	1690	424	134
" "	117	62.6	18.9	5.3	0.7	0.3	5.9	5.4	0.74	0.05	0.00	<15	150	8	9	1000	202	101
					$MgCO_3$	$CaCO_3$												
Knockainy	126	57.5	15.9	9.0	2.7	1.1	4.7	8.0	0.89	0.05	0.00	~15	45	12	9	2750	238	81
Ballynamona	127	56.4	18.1	10.2	2.4	7.4	4.4	4.5	1.00	0.16	0.12	20	55	13	9	1690	144	86
Killeenagalive	128	64.3	17.8	5.4	1.1	0.0	4.4	6.7	0.35	0.03	0.00	<15	126	<5	73	830	36	134
Cromwell	CP	61.6	17.0	5.6	1.9	2.7	4.1	6.6	0.36	0.07	0.00	<15	73	<5	34	650	<5	86
Longstone	129	66.1	17.5	4.3	0.2	0.3	4.9	6.5	0.28	0.01	0.00	~15	37	<5	24	350	<5	147
Carrickittle P10 (31.4m)	605	60.8	18.5	1.8	3.4	5.4	0.1	9.5	0.39	0.03	–	509	1490	10	12	–	–	–

			SiO_2	Al_2O_3	Fe_2O_3	$MgCO_3$	$CaCO_3$	Na_2O	K_2O	TiO_2	MnO	S	Pb	Zn	Cu	Ni	Ba	Sr	Rb
Carrickittle	P10 (32.9m)	606	61.7	19.5	6.1	1.7	1.3	0.1	9.3	0.41	0.00	2.27	540	450	<5	16	650	167	22
Oola	Q2 (148.4m)	473	44.4	20.2	2.4	1.5	23.6	0.1	5.1	2.48	0.13	0.23	<15	<5	15	13	500	85	125
	Q2 (152.7m)	474	38.8	18.0	7.2	3.0	26.1	0.2	4.4	2.13	0.20	0.17	<15	12	22	54	380	87	86
	Q3 (144.7m)	475	42.1	17.0	8.4	4.4	21.8	0.2	3.9	2.08	0.19	0.15	<15	112	<5	28	530	65	101
Gortdrum	G53 (48.8m)	991	38.6	11.6	4.3	4.1	37.6	0.2	2.9	0.63	0.20	0.38	<15	<5	48	51	210	116	80
	G139 (49.1m)	992	33.7	15.7	9.8	6.9	27.0	0.1	3.6	2.95	0.27	0.33	30	27	550	135	450	166	100
	G130 (65.8m)	993	51.7	8.3	6.7	8.3	20.2	0.1	3.0	1.53	0.12	0.28	<15	15	23	135	160	64	67
	G151 (9.1m)	994	32.9	10.0	11.9	10.5	30.3	0.0	2.0	2.17	0.19	0.45	<15	38	504	237	450	201	86

Gortdrum

Drill hole	Zone	Succession	Sp no.	Classification	Depth m
E7		Old Red Sandstone	854	Sandstone	22.8
B20A		Old Red Sandstone	832	Silt	15.2
		"	833	Sandstone	36.9
B19		Old Red Sandstone	836	Sandstone	21.9
		"	837	Shale	38.0
B18		Old Red Sandstone	834	Sandstone	21.3
		"	835	Sandstone	27.6
B16		Old Red Sandstone	880	Sandstone	41.7
B12		Old Red Sandstone	826	Sandstone	13.3
		"	827	Silt	16.4
		"	828	Silt	17.0
		"	830	Shale	21.6
		"	829	Sandstone	22.2
		"	831	Sandstone	24.6
B11		Old Red Sandstone	822	Silt	29.2
		"	824	Sandstone	33.5
B8		Old Red Sandstone	825	Sandstone	10.5
B22	K	Transition Lst	847	Limestone shale	6.1
	K	Upper Black Shale	848	Shaly limestone	7.6
	K	Calcareous Sand-stone	849	Calcareous sand-stone	10.3
		Old Red Sandstone	850	Sandstone	20.4
		"	851	Shale	22.9
B21	K	Transition Lst	865	Limestone shale	8.2
	K	Upper Black Shale	866	Shale	11.5
	K	Lower Black Shale	869	Shaly limestone	14.9
		Old Red Sandstone	868	Sandstone	19.2
		"	867	Sandstone	25.0
B25	K	Muddy Limestone	879	Limestone	10.8
	K	Muddy Limestone	852	Limestone	10.9
		Old Red Sandstone	853	Sandstone	18.9

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<15	<5	17	14	136	-	-	-	-	72	-	-	-	-	-
<15	17	<7	24	410	-	-	-	-	120	-	-	-	-	-
<15	16	<7	20	107	-	-	-	-	125	-	-	-	-	-
<15	~5	10	<7	1226	-	-	-	-	390	-	-	-	-	-
<15	7	22	58	225	98	175	-	-	170	-	-	-	-	-
<15	19	10	66	351	-	-	-	-	460	-	-	-	-	-
<15	~5	<7	<7	98	-	-	-	-	860	-	-	-	-	-
<15	<5	66	<7	4890	-	-	-	-	460	-	-	-	-	-
<15	15	12	27	1596	-	-	-	-	1600	-	-	-	-	-
<15	15	12	50	624	-	-	-	-	100000	-	-	-	-	-
20	18	14	51	1013	-	-	-	-	20000	-	-	-	-	-
<15	11	25	77	525	152	274	-	-	210	-	-	-	-	-
<15	6	415	15	180	-	-	-	-	880	-	-	-	-	-
<15	22	12	66	527	-	-	-	-	150	-	-	-	-	-
<15	24	10	78	292	-	-	-	-	860	-	-	-	-	-
<15	<5	18	37	955	-	-	-	-	10000	-	-	-	-	-
<15	27	990	9	7690	-	-	-	-	15000	-	-	-	-	-
33	44	27	68	295	168	109	-	-	1200	-	-	-	-	-
65	39	24	54	312	456	78	103	708	145	0.34	25.4	6.7	62.0	2.2
<15	17	16	21	1400	-	-	-	-	320	-	-	-	-	-
<15	17	41	24	273	-	-	-	-	350	-	-	-	-	-
<17	34	8	75	466	132	271	-	-	490	-	-	-	-	-
<17	6	27	41	290	146	108	103	-	320	0.22	48.1	13.1	29.4	2.3
<17	30	34	79	410	263	281	-	-	1300	-	-	-	-	-
81	32	8	40	282	227	70	26	702	50	0.20	23.1	5.7	66.1	1.4
<15	21	15	56	370	-	-	-	-	115	-	-	-	-	-
<15	18	20	39	2065	-	-	-	-	200	-	-	-	-	-
<17	18	18	23	230	570	24	-	-	-	-	-	-	-	-
<17	25	12	11	208	499	12	-	-	-	-	-	-	-	-
<15	107	450	52	350	-	-	-	-	-	-	-	-	-	-

	Zone	Succession	Sp no.	Classification	Depth m
B24	K	Transition Lst	855	Limestone	10.6
	K	Upper Black Shale	856	Shale	12.5
		Calcareous Sand-stone	857	Calcareous sand-stone	18.6
B31	K	Transition Lst	838	Limestone shale	19.8
	K	"	839	Limestone shale	25.9
	K	"	840	Limestone shale	33.2
	K	Upper Black Shale	841	Limestone shale	43.9
	K	Calcareous Sand-stone	842	Calcareous sand-stone	46.6
	K	Lower Black Shale	843	Limestone shale	50.0
	K	"	844	Limestone shale	51.3
		Old Red Sandstone	845	Sandstone	55.8
G145	K	Upper Black Shale	858	Shaly limestone	11.5
	K	Calcareous Sand-stone	859	Calcareous sand-stone	14.9
		Old Red Sandstone	860	Sandstone	20.7
		"	861	Sandstone	31.1
		"	862	Sandstone	35.0
		"	863	Sandstone	36.6
		"	864	Sandstone	51.5
G143	Z_1	Dark Limestone	881	Shaly limestone	8.8
B30	Z_1	Mudstone	870	Limestone shale	13.7
	K	Laminated Shale	871	Shaly limestone	30.8
	K	Transition Lst	872	Limestone	39.3
	K	Upper Black Shale	873	Limestone shale	42.7
	K	Calcareous Sand-stone	874	Calcareous sand-stone	45.4
	K	Lower Black Shale	875	Shale	48.5
G133	Z_1	Dark Limestone	877	Limestone shale	18.9

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
34	19	42	~8	215	-	-	-	-	460	-	-	-	-	-
69	18	37	60	365	-	-	-	-	400	-	-	-	-	-
<15	17	23	26	478	-	-	-	-	130000	-	-	-	-	-
<17	15	40	61	425	196	188	-	-	1400	-	-	-	-	-
120	11	22	25	340	367	-	49	-	400	0.11	31.7	8.5	52.9	2.7
17	11	24	16	195	-	-	-	-	50	-	-	-	-	-
345	57	24	37	330	492	107	46	547	100	0.16	34.0	10.1	47.5	2.3
<15	15	8	27	332	-	-	-	-	125	-	-	-	-	-
32	18	16	57	424	370	255	42	-	40	0.02	39.3	13.1	37.3	3.2
<17	20	21	58	465	88	258	-	-	300	-	-	-	-	-
<15	19	37	21	195	-	-	-	-	110	-	-	-	-	-
207	46	29	29	260	650	74	55	584	90	0.36	23.4	5.8	65.6	1.8
<15	40	12	52	370	-	-	-	-	450	-	-	-	-	-
<15	9	153	23	232	-	-	-	-	210	-	-	-	-	-
<15	23	23	63	390	-	-	-	-	100	-	-	-	-	-
<15	21	9	74	351	-	-	-	-	370	-	-	-	-	-
<15	17	<8	41	295	-	-	-	-	450	-	-	-	-	-
<15	22	<8	27	156	-	-	-	-	3000	-	-	-	-	-
480	48	18	88	272	494	74	145	703	1650	0.29	25.2	7.7	58.5	2.3
17	17	34	66	505	200	204	-	-	-	-	-	-	-	-
48	14	113	97	354	284	72	98	986	1000	0.72	34.4	8.5	46.2	5.1
110	21	18	38	220	345	21	117	944	530	0.19	26.9	3.8	64.3	1.1
106	30	20	60	360	448	146	84	464	240	0.24	36.1	10.7	42.1	3.5
<15	13	23	29	1500	-	-	-	-	235	-	-	-	-	-
37	23	18	72	375	-	-	-	-	1900	-	-	-	-	-
<17	55	20	69	404	344	136	-	-	350	-	-	-	-	-

Oola

Drill hole	Zone	Succession	Sp no.	Classification	Depth m
Q_2	Z_2	Pale Limestone	465	Limestone	3.9
		"	467	Limestone	34.4
		"	468	Limestone	43.9
		"	469	Limestone	86.0
	Z_1	Dark Limestone	471	Shaly limestone	134.1
		"	470	Shaly limestone	143.2
		"	472	Limestone	148.1
	K	Laminated Shale	475	Limestone	154.2
		"	476	Limestone	160.6
		"	477	Shale	168.5
		"	478	Limestone shale	170.0
		"	479	Limestone	190.8
	K	Transition Lst	480	Limestone	199.3
		"	481	Sandy limestone	202.7
	K	Upper Black Shale	482	Shale	206.6
	K	Calcareous Sdst	483	Calcareous sandstone	218.5
		"	484	Calcareous sandstone	225.6
		Old Red Sand-stone	485	Sandstone	241.2
		"	486	Sandstone	242.1
Q_3	Z_2	Pale Limestone	487	Limestone	22.8
		"	488	Limestone	50.6
		"	489	Limestone	74.1
	Z_1	Dark Limestone	490	Limestone	75.6
			491	Limestone	84.4
	K	Transition Lst	492	Limestone	127.7
			495	Limestone	153.3
			496	Shaly limestone	167.6
	K	Muddy Limestone	497	Limestone shale	181.1
			498	Shaly limestone	189.0
	K	Calcareous Sdst	499	Calcareous sandstone	204.8

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	147	19	18	500	447	~5	–	–	–	–	–	–	–
357	295	<8	35	168	427	22	41	192	0.05	9.5	2.7	84.6	0.9
75	20	12	13	190	370	~5	–	–	–	–	–	–	–
234	95	104	29	210	375	20	–	–	–	–	–	–	–
180	36	36	52	270	255	80	163	670	0.43	24.3	7.6	59.3	1.9
55	55	17	39	210	244	59	–	–	–	–	–	–	–
40	44	29	58	186	134	19	–	–	–	–	–	–	–
<17	431	19	14	168	322	<5	–	–	–	–	–	–	–
<17	76	13	10	236	247	13	–	–	–	–	–	–	–
<17	14	41	62	460	117	220	34	76	0.11	64.4	20.1	2.9	2.8
<17	12	<8	61	455	89	191	–	–	–	–	–	–	–
<17	6	9	20	356	376	<5	–	–	–	–	–	–	–
<17	21	<8	29	247	230	28	48	1350	0.08	23.2	4.3	58.6	4.3
<17	15	<8	30	234	–	–	–	–	–	–	–	–	–
25	19	20	49	385	358	204	–	–	–	–	–	–	–
<15	13	180	40	244	–	–	–	–	–	–	–	–	–
<15	17	15	40	232	–	–	–	–	–	–	–	–	–
<15	<5	<8	15	916	–	–	–	–	–	–	–	–	–
<15	18	<8	43	410	–	–	–	–	–	–	–	–	–
24	77	12	20	404	392	19	–	–	–	–	–	–	–
<17	542	20	48	598	335	35	43	184	0.11	16.3	4.5	73.1	2.1
24	69	11	17	154	323	10	–	–	–	–	–	–	–
32	101	<8	19	190	273	14	34	333	0.19	16.2	3.4	74.8	1.2
102	69	9	20	230	412	9	–	–	–	–	–	–	–
160	253	64	39	218	268	5	221	344	0.08	3.8	0.7	89.7	3.2
<17	101	15	21	–	–	–	–	–	–	–	–	–	–
<17	21	24	34	346	320	54	~25	675	0.14	20.9	5.6	61.9	4.3
<17	17	23	65	410	202	180	65	472	0.26	55.9	16.6	14.7	4.2
39	16	19	84	334	234	60	196	774	0.41	39.1	6.9	43.9	3.6
165	30	<8	18	196	368	<5	–	–	–	–	–	–	–

GORTDRUM NORTH AUREOLE IN LIMESTONES AND LIMESTONE SHALES, AND SUMMARY OF RESULTS OF ANALYSES OF SIMILAR ROCKS FROM OOLA, CASTLEISLAND, PALLASKENRY AND HOOK HEAD

B30	Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
n	5	5	5	5	5	4	4	3	3	3	3	3	3	3	3
R	~17-110	14- 30	18-113	38-97	220-505	200-448	21-204	84-117	464-986	240-1000	0.19-0.72	26.9-36.1	3.8-10.7	42.1-64.3	1.1-4.1
M	64	21	41	67	363	319	111	100	798	590	0.38				2.9
B31															
n	6	6	6	6	6	5	4	3	1	5	3	3	3	3	3
R	<17-345	11-57	16-40	16-61	195-465	88-492	107-248	42-49	547	40-1400	0.02-0.16	31.7-39.3	8.5-13.1	37.5-52.9	2.3-3.2
M	87	22	25	42	363	303	202	46		380	0.10				2.7
G133 G143 G145															
n	3	3	3	3	3	3	3	2	2	3	2	2	2	2	2
R	<17-480	46-55	18-29	29-88	260-404	344-650	74-136	55-145	584-703	100-1650	0.29-0.36	23.2-25.2	5.8-7.7	58.5-65.6	1.8-2.3
M	231	50	22	62	312	496	95	100	644	700	0.33				2.1
B22 B21 B25 B24															
n	9	9	9	9	9	7	7	3	2	7	3	3	3	3	3
R	<17-81	6-44	<8-42	<8-79	208-410	146-570	12-281	26-103	702-708	50-1300	0.20-0.34	23.1-48.1	5.7-13.1	29.4-66.1	1.4-2.3
M	35	26	25	42	290	333	97	77	705	555	0.25				2.0
Q3 Oola															
n	10	10	10	10	9	9	9	6	6	–	6	6	6	6	6
R	<17-160	16-542	<8-64	17-84	154-598	202-412	<5-180	~25-221	184-774		0.08-0.41	3.8-55.9	0.7-16.6	14.7-89.7	1.2-4.3
M	44	127	20	37	320	307	43	97	464		0.20				3.9
Q2 Oola															
n	15	15	15	15	15	14	14	4	4	–	4	4	4	4	4
R	<17-357	6-431	<8-104	13-62	168-500	89-447	<5-220	34-163	76-1350		0.05-0.43	9.5-64.4	2.7-20.1	2.9-84.6	0.9-4.3
M	69	79	22	35	285	292	62	72	572		0.17				2.5
South Shannon															
n	36	36	36	36	29	29	29	18	18	12	18	18	18	18	18
R	<17-57	<6-447	<8-66	<8-116	160-880	57-1764	<5-302	<25-167	74-1739	34-295	0.02-0.46	4.1-64.6	1.2-19.6	0.0-88.8	1.2-7.2
M	~21	75	21	40	408	616	98	21	675	106	0.12				4.7
Castleisland															
n	4	4	4	4	3	2	2	1	1	–	1	1	1	1	1
R	<17-20	<6-115	9-33	<8-84	150-468	215-345	<5-13	28	<30		.02	5.6	0.4	91.5	0.3
M	≤17	34	16	26	272	280	~8								

	Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<u>Hook Head</u>															
n	16	16	16	16	11	11	11	6	6	5	6	6	6	6	6
R	<17-40	<6-96	<8-45	<8-86	200-535	79-513	<5-222	<25-138	26-2307	29-48	0.02-0.50	4.5-65.8	0.8-20.2	0.0-89.2	1.1-6.6
M	~17	40	15	36	359	229	105	~51	643	39	0.20				5.0

Carrickittle

Drill hole	Zone	Succession	Sp no	Classification	Depth (m)
		Waulsortian Bank	504	Waulsortian	7.6
		Complex	505	limestone	25.3
P33			506	"	41.4
			507	"	54.0
			580	"	61.6
			581	"	63.1
			582	"	64.3
			583	"	65.8
			508	"	67.1
			584	"	69.2
			585	"	70.7
			586	"	74.1
			591	"	83.6
			594	"	84.8
			593	"	100.6
			592	"	103.7
	?	Sub-Waulsortian	509	Limestone	123.4
			595	"	124.9
			596	"	126.4
P30	?	Waulsortian Bank	501	Waulsortian lime-	18.3
		Complex	502	stone	27.5
			503	"	45.7
P27	?	Waulsortian Bank	500	Waulsortian lime-	35.3
		Complex	601	stone	36.9
			602	"	41.4
			600	"	47.2
			598	"	49.7
			599	"	53.9
			597	"	55.2
P9	?	Waulsortian Bank	609	"	12.2
		Complex			

Pb	Zn	Cu	Ni	Ba	Sr	Rb	Mn	Hg	S	Fe_2O_3
<17	<6	<8	<8	210	163	<5	<30	–	0.04	0.1
<17	<6	10	~8	186	155	<5	–	–	–	–
<17	<6	11	<8	194	180	<5	–	–	–	–
<17	34	<8	<8	184	163	<5	–	–	–	–
<17	<6	<6	<8	210	161	<5	–	26	–	–
<17	8	<8	26	192	193	<5	<30	31	0.03	0.1
<17	<6	<8	10	164	173	<5	–	45	–	–
<17	29	<8	<8	150	135	<5	–	–	–	–
<17	18	<8	9	130	84	<5	–	–	–	–
<17	<6	13	<8	196	158	<5	–	38	–	–
<17	<6	17	9	186	149	<5	–	32	–	–
<17	24	<8	~8	186	133	<5	–	24	–	–
<17	90	10	26	186	126	<5	589	150	0.06	0.9
<17	54	<8	16	169	147	<5	–	–	0.00	1.0
<17	45	16	<8	185	162	<5	–	–	0.00	0.3
23	153	<8	44	171	108	10	–	–	–	–
<17	30	16	10	186	159	<5	–	–	–	–
~17	21	11	<8	192	140	<5	–	25	0.0	0.2
<17	16	<8	<8	176	163	<5	–	39	–	–
<17	<6	<8	<8	166	38	<5	1168	–	0.10	1.9
<17	51	<8	<8	184	31	<5	1227	–	0.18	1.6
<17	145	28	10	210	25	<5	907	–	0.11	1.5
21	78	55	14	192	74	<5	1440	–	0.02	1.4
<17	39	<8	~8	180	127	<5	–	–	–	–
<17	435	12	20	214	27	<5	1488	<20	0.14	2.0
103	800	43	20	244	7	<5	691	37	0.12	4.7
<17	610	114	28	208	~5	<5	104	35	0.06	1.7
<17	42	<8	<8	159	152	<5	–	–	–	–
58	335	<8	62	185	139	<5	–	–	–	–
1960	9000	10	12	183	68	<5	–	–	–	–

	Zone	Succession	Sp no	Classification	Depth (m
P18	?	Waulsortian Bank	532	Waulsortian	32.0
(dip 50 W)		Complex	531	limestone	35.0
			530	" "	37.2
			529	" "	38.1
			528	" "	39.0
		ORE & INTRUSIVES			
	?	Waulsortian Bank	533	Waulsortian	75.4
		Complex	534	limestone	78.6
			535	" "	80.8
			536	" "	85.4
P17	?	Waulsortian Bank	521	Waulsortian	9.1
		Complex	520	limestone	12.2
			519	" "	17.7
			518	" "	21.3
			517	" "	22.8
			516	" "	24.1
			515	" "	25.0
			514	" "	25.9
			513	" "	26.9
			512	" "	27.5
			511	" "	27.8
			510	" "	28.1
		ORE			
		Transition Lime-stone	522	Limestone	38.4
			523	Shaly Limestone	39.6
		Streaky Limestone	524	Limestone	41.1
			525	Shaly limestone	42.7
			526	Limestone shale	45.1
Carrickittle	?	Waulsortian Bank	540	Waulsortian	
Rock		Complex	543	limestone	
Cool House		Waulsortian Bank	544	Waulsortian	
		Complex	545	limestone	

Pb	Zn	Cu	Ni	Ba	Sr	Rb	Mn	Hg	S	Fe_2O_3
<17	23	13	11	180	190	<5	–	–	–	–
<17	69	~8	11	–	–	–	–	–	–	–
57	156	17	10	188	175	<5	30	–	0.14	0.3
<17	92	12	<8	194	193	<5	31	–	0.05	0.2
21	212	~8	12	198	122	<5	256	–	0.18	1.1
540	267	11	11	180	118	<5	866	–	0.18	1.3
70	655	16	17	220	132	57	–	–	–	–
25	221	11	23	186	180	<5	107	–	0.09	0.5
<17	16	16	<8	158	200	<5	51	–	0.01	0.1
<17	16	<8	16	148	119	<5	–	–	–	–
<17	24	17	13	184	175	<5	–	40	–	–
<17	16	<8	<8	188	178	<5	–	29	–	–
<17	14	<8	<8	174	246	<5	–	–	–	–
<17	42	~8	11	194	182	<5	–	–	–	–
<17	14	30	<8	180	165	<5	78	38	0.07	0.5
<17	13	<8	<8	200	147	<5	134	43	0.13	0.9
<17	11	11	<8	200	20	<5	68	–	0.05	0.2
<17	36	13	32	186	198	<5	126	42	0.07	0.4
<17	41	17	13	186	212	<5	170	–	0.03	0.3
33	139	20	<8	160	146	<5	150	–	0.02	0.4
172	237	<8	<8	155	144	<5	141	–	0.10	0.6
22	72	12	18	216	152	20	648	22	0.10	1.0
<17	32	~8	44	242	151	50	588	–	0.06	1.4
<17	128	15	33	194	154	16	673	41	0.10	1.1
<17	66	13	48	232	188	61	810	45	0.22	1.6
20	21	45	115	305	107	–	107	–	–	–
<17	<6	<8	15	210	128	<5	–	20	–	–
<17	<6	<8	~8	180	174	7	–	20	–	–
<17	<6	<8	<8	198	136	<5	–	25	–	–
<17	<6	15	15	166	155	<5	–	24	–	–

Samples from Waulsortian Bank complex outcrop west and northwest of Tynagh Mine	Sp no.	Bearing from Tynagh mine°	Distance from Tynagh, km
	779	259	4.0
	780		
	783	280	4.7
	784		
	785		
	792	300	4.9
	793		
	788	291	5.5
	789		
	790	312	5.5
	782	270	6.2
	786	285	6.4
	787		
	794	296	6.7
	795		
	797	290	8.3
	798	285	9.5
	799		
	802	300	10.0
	803		
	800	295	11.2
	801		

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
22	<6	20	12	180	151	~5	<25	648	32	0.06	1.6	0.6	95.6	0.48
<17	<6	<8	9	256	144	29	—	—	26	—	—	—	—	—
<17	10	<8	35	194	240	8	—	—	~20	—	—	—	—	—
<17	<6	<8	15	194	272	16	<25	648	27	0.01	3.5	1.2	92.5	0.53
<17	<6	19	<8	204	197	<5	—	—	52	—	—	—	—	—
<17	8	<8	18	154	192	<5	25	395	<20	0.00	0.4	0.3	98.3	0.12
<17	10	<8	16	196	186	<5	—	—	21	—	—	—	—	—
<17	13	<8	20	166	197	<5	—	—	36	—	—	—	—	—
<17	7	15	11	186	190	<5	—	—	33	—	—	—	—	—
<17	<6	16	<8	188	203	<5	—	—	<20	—	—	—	—	—
<17	<6	10	<8	184	164	<5	~25	324	<20	0.00	0.6	0.4	98.2	0.17
<17	8	<8	13	178	169	<5	—	—	<20	—	—	—	—	—
<17	<6	<8	16	176	179	~5	35	389	<20	0.00	1.0	0.5	96.7	0.19
<17	15	<8	10	172	197	<5	—	—	<20	—	—	—	—	—
<17	<6	16	<8	194	201	<5	—	—	~20	—	—	—	—	—
<17	~6	9	15	198	167	<5	<25	136	23	0.00	0.7	0.4	97.8	0.17
<17	<6	21	<8	184	160	<5	—	—	23	—	—	—	—	—
<17	<6	<8	26	160	163	<5	35	248	<20	0.00	0.4	0.3	87.0	0.13
22	9	<8	33	190	212	<5	—	—	<20	—	—	—	—	—
<17	<6	<8	<8	156	199	<5	—	—	<20	—	—	—	—	—
<17	<6	15	<8	184	187	<5	<25	119	25	0.04	0.3	0.4	94.0	0.21
<17	9	13	24	194	163	<5	35	123	27	0.03	1.8	0.9	90.1	0.44

Tynagh Mine Area	Succession	Sp no.	Classification	Depth m
179	Calp	695	Limestone	6.1
		696	Limestone	88.7
	Waulsortian equivalents	697	Pseudo breccia	342.3
		698	Pseudo breccia	372.5
	Muddy	704	Shaly limestone	471.5
	Limestone	703	Limestone shale	615.7
		702	Limestone	691.3
	Old Red	701	Calcareous sandstone	709.3
	Sandstone	700	Sandstone	712.6
157A	Calp	659	Limestone	18.3
	Waulsortian Bank	660	Shaly limestone	238.4
	Complex	662	Shaly limestone	241.5
	Waulsortian equivalents	661	Off Reef Limestone	246.1
	Muddy Limestone	663	Limestone	260.5
		664	Shaly limestone	274.6
153	Calp	652	Limestone	1.2
		653	Limestone shale	208.8
	Waulsortian Bank Complex	654	Shaly limestone	217.6
	Waulsortian equivalents	668	Pseudo breccia	274.9
	Muddy Limestone	657	Limestone shale	294.4
149	Calp	647a	Limestone	7.5
		647b	Limestone	7.6
	Green tuff	648	Tuff	177.1
	Muddy Limestone	651	Limestone shale	252.6
152	Calp	644	Limestone	4.8
		637	Shaly limestone	54.9
		636	Limestone	60.7

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	<6	29	22	214	1283	8	<25	<30	142	0.26	24.6	1.4	67.7	0.6
<17	<6	18	11	206	880	<5	–	–	40	–	–	–	–	–
<17	16	30	84	234	366	40	25	2458	38	0.12	42.9	3.6	46.8	2.2
<17	28	36	35	278	256	75	29	1653	90	0.19	36.8	6.4	46.4	3.9
~17	21	43	52	216	959	54	34	128	48	0.30	43.0	4.5	45.1	3.1
<17	21	31	47	356	360	117	<25	699	74	0.17	26.1	6.9	57.1	3.6
<17	15	<8	<8	242	329	21	–	–	<20	–	–	–	–	–
<17	<6	12	16	698	104	107	~25	723	64	0.09	66.8	9.7	9.8	1.9
<15	<6	17	19	750	104	103	–	–	74	–	–	–	–	–
<17	190	<8	46	191	840	<5	–	–	30	–	–	–	–	–
<17	29	12	78	254	319	55	–	3006	~20	0.00	17.7	3.6	69.5	3.5
<17	205	11	30	234	246	47	35	4570	<20	0.11	51.7	1.9	42.7	1.0
<17	25	9	37	230	289	17	–	–	112	–	–	–	–	–
<17	20	20	77	250	350	36	39	1448	<20	0.03	29.6	3.5	58.4	4.2
21	30	<8	77	309	405	82	–	–	~20	–	–	–	–	–
<17	35	28	41	194	977	6	29	<30	106	0.24	20.7	1.4	70.4	0.7
99	44	29	185	446	483	160	169	4000	64	0.21	40.3	8.2	39.9	4.0
<17	103	19	93	300	357	81	–	–	30	–	–	–	–	–
34	48	65	52	396	295	159	85	1318	56	0.18	33.4	7.7	46.8	5.0
<17	55	27	199	564	302	229	80	691	56	0.19	48.5	13.9	18.3	9.8
<17	64	<8	80	203	1230	<5	–	–	<20	–	–	–	–	–
<17	24	<8	43	233	1280	12	–	–	–	–	–	–	–	–
<17	65	<8	63	–	–	–	–	–	74	–	–	–	–	–
225	145	64	152	490	337	219	518	854	106	0.13	38.2	10.4	38.5	5.4
<17	37	16	24	274	360	13	–	–	40	–	–	–	–	–
18	72	<8	685	338	225	42	–	–	56	–	–	–	–	–
<17	94	17	69	226	205	11	–	–	<20	–	–	–	–	–

	Succession	Sp no.	Classification	Depth m
	Waulsortian Bank	638	Waulsortian Limestone	84.4
	Complex	640	"	93.6
		639	"	99.4
		641	"	103.0
	Tuff	633	Tuff	118.4
	Waulsortian Bank Complex	645	Shaly limestone	158.5
	Muddy Limestone	646	Limestone shale	173.1
146	Calp	665	Limestone	14.3
		667	Limestone	49.5
		666	Limestone	54.9
	Waulsortian equiva-	670	Pseudo breccia	111.5
	lent	672	Shaly limestone	119.2
	Mineralization			
96	Calp	673	Limestone	13.1
		674	"	21.6
		675	"	28.1
		676	"	41.9
		677	"	52.4
	Waulsortian Bank	678	Waulsortian	74.1
	Complex		Limestone	
		679	"	101.9
		681	"	127.9
		682	"	129.5
72	Calp	728	Limestone	6.7
	Calp	729	"	30.5
	Mineralization			
107	Waulsortian Bank	725	Waulsortian	10.9
	Complex		Limestone	
		726	"	29.0
	Mineralization			

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
31	37	17	39	264	27b	8	—	—	<20	—	—	—	—	—
40	1518	11	16	256	241	12	29	6600	~20	0.16	3.0	0.8	91.3	1.0
90	186	18	55	262	298	25	87	5305	136	0.59	18.0	2.0	70.7	4.4
28	119	25	67	—	—	—	70	2427	<20	0.10	12.3	2.4	76.2	3.9
176	188	10	40	—	—	—	—	—	50	—	—	—	—	—
<17	34	20	36	506	355	82	—	—	30	—	—	—	—	—
42	48	46	174	986	297	326	175	853	74	0.18	53.3	16.0	14.6	5.1
<17	456	30	80	396	301	24	—	—	<20	—	—	—	—	—
<17	7	~8	78	278	234	12	28	8270	<20	0.22	22.8	0.9	68.7	0.9
<17	1262	22	18	256	200	<5	—	—	<20	—	—	—	—	—
27	97	11	29	356	298	45	—	—	152	—	—	—	—	—
219	610	16	36	726	321	46	—	—	98	—	—	—	—	—
<17	78	9	55	386	206	16	—	—	<20	—	—	—	—	—
~17	161	17	68	276	213	14	<25	9700	<20	0.25	19.9	0.8	71.8	0.7
46	120	27	90	384	163	19	—	—	590	—	—	—	—	—
~17	16	13	245	294	227	15	77	5970	~20	0.23	26.8	1.0	67.0	1.3
<17	18	9	<8	218	219	<5	—	—	<20	—	—	—	—	—
<17	670	<8	10	266	204	<5	45	1610	<20	0.09	1.4	0.6	92.7	0.5
<17	12	18	<8	394	394	19	—	—	38	—	—	—	—	—
196	440	20	12	184	625	10	—	—	<20	—	—	—	—	—
<17	3900	22	24	1414	630	15	68	2257	~20	0.20	5.3	1.6	83.0	2.8
27	299	17	232	622	265	19	460	12900	400	3.25	7.7	2.2	67.6	10.1
84	14	21	<8	278	317	<5	85	1178	<20	0.01	1.8	0.3	96.4	2.8
<17	55	~8	10	274	219	<5	—	—	<20	—	—	—	—	—
~17	3660	10	13	380	211	<5	351	971	400	1.60	0.8	0.3	90.1	5.4

	Succession	Sp no.	Classification	Depth m
121	Waulsortian Bank	734	Waulsortian Limestone	22.2
	Complex	735	" "	64.3
	(Minor mineralization)			
126	Waulsortian Bank	731	Waulsortian limestone	17.3
	Complex	732	" "	67.7
		733	Shaly limestone	91.2
155	Waulsortian Bank	730	Waulsortian limestone	8.2
	(Minor mineralization)			
159	Calp	683	Limestone	7.6
	Waulsortian equiva-lent	684	Pseudo breccia	49.4
	Waulsortian Bank Complex	685	Waulsortian limestone	73.2
	Waulsortian equiva-lent	687	Pseudo breccia	94.5
	Muddy Limestone	688	Limestone	137.1
182	Calp	765	Shaly Limestone	13.4
	Waulsortian Bank	766	Waulsortian limestone	39.6
	Complex			
	Muddy Limestone	767	Limestone shale	137.1
186	Calp	716	Limestone	32.6
	Waulsortian Bank	717	Waulsortian limestone	49.4
	Complex	718	" "	62.2
		719	" "	66.1
	Muddy Limestone	720	Limestone	104.3
187	Muddy Limestone	705	Shaly limestone	11.2
		706	Limestone	20.4
		707	Shaly limestone	28.1
		708	" "	36.0
		711	Limestone	42.7
		710	"	44.2
		709	Shaly limestone	46.0
		715	" "	57.4
	Lower Limestone	714	Limestone shale	76.5
	Shales	713	" "	77.1
		712	" "	78.4

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	28	12	~8	326	221	6	41	670	<20	0.02	1.0	0.5	96.9	2.7
~17	44	9	10	396	244	<5	42	611	<20	0.01	0.8	0.4	97.5	0.2
225	4360	12	24	840	274	<5	61	874	<20	0.33	0.4	0.3	94.6	0.4
24	4800	22	41	166	180	6	–	–	<20	–	–	–	–	–
<17	84	<8	<8	1410	366	51	–	–	–	–	–	–	–	–
189	76	31	47	264	260	<5	53	2832	<20	0.08	13.1	0.2	83.3	0.5
<17	462	20	28	116	94	<5	38	6900	30	0.20	45.1	0.3	31.9	0.8
24	11	24	107	314	268	50	129	2327	–	0.05	20.6	2.8	71.8	1.5
<17	21	<8	20	306	223	19	–	–	136	–	–	–	–	–
25	64	22	152	4500	297	261	–	1152	40	0.02	28.9	8.4	53.0	2.6
24	257	19	32	298	452	33	38	2074	<20	0.18	23.9	2.4	65.3	4.2
33	90	23	185	305	530	99	–	–	<20	–	–	–	–	–
<17	111	22	66	206	258	33	–	–	60	–	–	–	–	–
<17	299	31	113	410	435	169	<25	189	120	0.43	45.0	12.3	27.4	6.1
<17	7	12	70	147	402	15	36	2405	<20	0.02	20.8	1.7	73.1	1.4
<17	<6	9	10	145	158	<5	–	–	<20	–	–	–	–	–
<17	~6	12	12	220	174	6	–	–	~20	–	–	–	–	–
<17	<6	12	28	210	236	15	<25	841	<20	0.00	8.5	1.4	86.6	0.9
<17	44	16	41	196	662	24	<25	898	<20	0.06	19.0	2.5	72.8	2.5
25	30	19	49	265	647	77	–	–	98	–	–	–	–	–
<17	53	21	43	246	842	33	–	–	56	–	–	–	–	–
<17	87	20	68	255	812	51	–	–	30	–	–	–	–	–
19	57	12	69	297	582	72	–	–	136	–	–	–	–	–
23	71	12	28	238	571	29	–	–	<20	–	–	–	–	–
<17	62	9	23	190	610	11	–	–	152	–	–	–	–	–
<17	74	24	53	224	958	70	–	–	56	–	–	–	–	–
36	266	20	34	270	597	41	60	226	74	0.57	12.8	3.1	76.2	1.7
57	44	<8	44	902	553	191	–	–	144	–	–	–	–	–
63	51	27	65	830	522	138	–	–	135	–	–	–	–	–
110	62	46	62	1147	237	289	72	1190	220	0.50	37.3	11.3	39.1	5.0

	Succession	Sp no.	Description	Depth m
168	Calp	745	Limestone	15.8
		746	"	142.0
	Waulsortian equivalent	747	Waulsortian Limestone	157.5
	Muddy Limestone	744	Shale	212.8
185	Waulsortian Bank	760	Waulsortian Limestone	6.7
	Complex	762	" "	37.2
	Muddy Limestone	763	Limestone	106.4
		764	"	128.3
166	Waulsortian Bank	740	Waulsortian Limestone	10.9
	Complex	742	" "	17.2
		741	" "	29.2
	Muddy Limestone	743	Limestone shale	86.0
169	Muddy Limestone	736	Limestone shale	10.9
		737	Limestone	29.6
		738	Limestone	59.2
		739	Shaly limestone	77.4
ST4	Waulsortian Bank	918	Waulsortian Limestone	18.6
	Complex	919	" "	24.7
	(Transition)	920	Limestone	32.3
ST3	Waulsortian Bank	912	Waulsortian Limestone	25.3
	Complex	913	Shaly limestone	32.3
		914	Waulsortian Limestone	39.6
		915	" "	45.7
	(Transition)	916	Limestone	53.9
	(Transition)	917	Limestone shale	59.2
162	Calp	689	Shaly limestone	6.4
	Waulsortian Bank	690	Shaly limestone	29.0
	Complex	691	Waulsortian limestone	29.9
	Waulsortian equivalent	692	Pseudo breccia	52.7
	Muddy Limestone	693	Limestone shale	67.1
		694	" "	91.8

Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
<17	<6	11	9	102	521	<5	–	–	<20	–	–	–	–	–
<17	<6	~8	69	206	256	12	59	4842	40	0.22	20.6	1.0	76.0	0.8
<17	<6	22	43	256	161	38	–	–	<20	–	–	–	–	–
<17	27	39	73	830	89	141	65	3312	<20	0.05	55.1	13.1	2.4	19.2
<17	92	20	67	250	299	19	<25	1394	<20	0.09	23.5	2.2	68.5	2.2
<17	9	17	56	240	566	26	–	–	40	–	–	–	–	–
34	11	<8	27	364	381	-	32	672	30	0.23	31.3	6.4	54.1	3.2
<17	21	17	24	232	440	20	–	–	56	–	–	–	–	–
<17	11	<8	65	217	498	32	–	–	<20	–	–	–	–	–
<17	28	~8	73	246	265	38	–	–	<20	–	–	–	–	–
74	1240	28	177	244	436	15	26	1018	<20	0.32	19.8	2.4	69.4	4.2
37	25	39	91	430	670	198	<25	136	74	0.27	43.2	11.8	29.4	5.2
~17	14	26	63	426	442	105	<25	258	60	0.46	28.1	7.7	53.1	3.0
<17	7	20	23	276	893	32	–	–	<20	–	–	–	–	–
<17	<6	~8	<8	224	529	7	–	–	~20	–	–	–	–	–
24	179	19	33	500	426	66	<25	682	60	0.28	35.8	7.0	45.8	3.4
<17	<6	<8	14	222	195	10	–	–	–	–	–	–	–	–
<17	21	17	52	194	366	26	–	–	–	–	–	–	–	–
<17	97	9	50	238	462	14	–	1294	–	0.10	21.9	2.0	69.0	2.4
<17	57	29	124	260	541	23	–	–	–	–	–	–	–	–
30	32	27	213	316	507	44	–	–	–	–	–	–	–	–
<17	32	10	56	240	402	12	–	–	–	–	–	–	–	–
<17	16	9	36	250	485	10	–	–	–	–	–	–	–	–
<17	23	24	54	–	–	–	–	–	–	–	–	–	–	–
18	80	31	180	338	449	120	–	–	–	–	–	–	–	–
29	91	33	148	255	498	59	<25	1624	184	0.25	39.0	5.2	46.7	2.8
<17	14	58	70	212	329	53	<25	1930	<20	0.12	16.1	1.7	76.0	1.9
<17	34	10	76	248	318	32	–	–	<20	–	–	–	–	–
20	46	50	95	292	414	64	29	1763	<20	0.13	27.3	5.6	56.7	3.5
18	162	19	163	390	493	149	–	–	106	–	–	–	–	–
~17	34	39	125	330	445	176	~25	148	112	0.24	50.9	13.5	18.9	6.4

TYNAGH: SUMMARY OF RESULTS

Calp

Drill hole		Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
179	n	2	2	2	2	2	2	2	1	1	2	1	1	1	1	1
	R	<17	<6	18-29	11-22	206-214	1283-880	<5-8	<25	<30	40-142	0.26	24.6	1.4	67.7	0.7
	M	<17	<6	24	17	210	1082	~5			91					
157A	n	1	1	1	1	1	1	1	–	–	1	–	–	–	–	–
	R	<17	190	<8	46	191	840	<5			30					
153	n	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	R	<17-99	35-44	28-29	41-185	194-446	483-977	6-160	29-169	<30-4000	64-106	0.21-.28	20.7-40.3	1.4-8.2	39.9-70.4	0.7-4.0
	M	54	40	29	113	320	730	83	99		85	0.25				2.4
149	n	2	2	2	2	2	2	2	–	–	2	–	–	–	–	–
	R	<17	24-64	<8	43-80	203-233	1230-1280	<5-12			<20					
	M	<17	44	<8	62	218	1255	~7								
152	n	3	3	3	3	3	3	3	–	–	3	–	–	–	–	–
	R	<17-18	37-94	<8-17	69-685	226-338	205-360	11-42			<20-56					
	M	≤17	68	~12	259	279	263	22			~35					
146	n	3	3	3	3		3	1	1	1	3	1	1	1	1	1
	R	<17	7-1262	8-30	18-80	256-396	200-301	<5-24	28	8270	<20	0.22	22.8	0.9	69	0.9
	M	<17	575	20	59	310	245	13								
96	n	5	5	5	5	5	5	5	2	2	5	2	2	2	2	2
	R	<17-46	16-161	9-27	8-245	218-386	163-227	<5-19	<25-77	5970-9700	<20-590	0.23-25	19.9-26.8	0.8-1.0	67.0-71.8	0.7-1.3
	M	~19	59	15	92	312	206	~14	~51	7835	~128	0.24				0.1
72	n	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	R	27-84	14-299	17-21	<8-232	278-622	265-317	<5-19	85-460	1178-12900	<20-400	0.01-3.25	1.8-7.7	0.3-2.2	67.6-96.4	2.8-10.1
	M	56	157	19	118	450	291	~11	273	7039	~205	1.63				6.5
159	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	<17	462	20	28	116	94	<5	38	6900	30	0.20	45.1	0.3	31.9	0.8
182	n	1	1	1	1	1	1	1	–	–	1	–	–	–	–	–
	R	33	90	23	185	305	530	99			<20					
186	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	<17	7	12	70	147	402	15	36	2405	<20	0.02	20.8	1.7	73.1	1.4
168	n	2	2	2	2	2	2	2	1	1	2	1	1	1	1	1
	R	<17	<6	~8-11	9-69	102-206	256-521	<5-12	59	4842	<20-40	0.22	20.6	1.0	76.0	0.8
	M	<17	<6	10	39	154	389	~7			~25					
162	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	29	91	33	148	255	498	59	<25	1624	184	0.25	39.0	5.2	46.7	2.8

Waulsortian Bank Complex and equivalents

		Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
Outcrop northwest of Tynagh	n	22	22	22	22	22	22	22	9	9	22	9	9	9	9	9
	R	<17-22	<6-15	<8-21	<8-35	154-256	144-272	<5-29	<25-35	70-648	<20-52	0.00-0.06	0.3-3.5	0.3-1.2	87.0-98.3	0.12-0.53
	M	<17	<6	~8	13	186	188	≤5	≤25	321	~22	0.01				0.27
Drill hole																
179	n	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	R	<17	16-28	30-36	35-84	234-278	256-366	40-75	<25-29	1653-2458	38-90	0.12-0.19	36.8-42.9	3.6-6.4	46.4-46.8	2.2-3.9
	M	<17	22	33	60	256	311	58	≤25	2056	64	0.16				3.1
157A	n	3	3	3	3	3	3	3	1	2	3	2	2	2	2	2
	R	<17	25-205	19-12	30-78	230-254	246-319	17-55	35	3006-4570	<20-112	0.00-0.11	17.7-51.7	1.9-3.6	42.7-69.5	1.0-3.5
	M	<17	86	11	48	239	285	40		3788	~47	0.06				2.3
153	n	17	2	2	2	2	2	2	1	1	2	1	1	1	1	1
	R	<17-34	48-103	19-65	52-93	300-396	295-357	81-159	85	1318	30-56	0.18	33.4	7.7	46.8	5.0
	M	~21	76	42	73	348	326	120			43					
152	n	5	5	5	5	4	4	4	3	3	5	3	3	3	3	3
	R	17-90	34-1518	11-25	16-67	256-506	241-355	8-82	29-87	2427-6600	<20-136	0.10-0.59	3.0-18.0	0.8-2.4	70.7-91.3	0.9-4.4
	M	39	379	18	43	322	293	32	62	4777	~41	0.28				3.1
146	n	2	2	2	2	2	2	2	–	–	2	–	–	–	–	–
	R	27-219	97-610	11-16	29-36	356-726	298-321	45-46			98-152					
	M	123	354	14	33	541	310	46			125					
96	n	4	4	4	4	4	4	4	2	2	4	2	2	2	2	2
	R	<17-196	12-3900	<8-22	<8-24	266-1414	204-630	<5-19	45-68	1610-2257	<20-38	0.09-0.20	1.4-5.3	0.6-1.6	83.0-92.7	0.5-2.8
	M	~55	1255	~16	~12	565	463	~12	57	1934	~20	0.15				1.7
72	(Mineralized)															
107	n	2	2	2	2	2	2	2	1	1	2	1	1	1	1	1
	R	<17-~17	55-3660	~8-10	10-13	274-380	211-219	<5	351	971	<20-400	1.6	0.8	0.3	90.1	5.4
	M	<17	1858	9	12	327	215	<5			~205					
121	n	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	R	<17-17	28-44	9-12	8-10	326-396	221-244	<5-6	41-42	611-670	<20	0.01-0.02	0.8-1.0	0.4-0.5	96.9-97.5	0.2-2.7
	M	<17	36	11	9	361	233	≤5	42	641	<20	.02				1.5
126	n	3	3	3	3	3	3	3	1	1	2	1	1	1	1	1
	R	<17-225	84-4800	<8-22	<8-41	166-1410	180-366	<5-51	61	874	<20	0.33	0.4	0.3	94.6	0.4
	M	~86	3081	~13	~23	805	273	~20			<20					
155	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	189	76	31	47	264	260	<5	53	2832	<20	0.08	13.1	0.2	83.3	0.5

Drill hole		Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
159	n	3	3	3	3	3	3	3	1	2	2	2	2	2	2	2
	R	<17-25	11-64	<8-24	20-152	306-4500	223-297	19-261	129	1152-2327	40-136	0.02-0.05	20.6-28.9	2.8-8.4	53.0-71.8	1.5-2.6
	M	~19	32	~16	92	1707	263	110		1735	88	0.04				2.1
182	n	1	1	1	1	1	1	1	—	—	1	—	—	—	—	—
	R	<17	111	22	66	206	258	33			60					
186	n	3	3	3	3	3	3	3	1	1	3	1	1	1	1	1
	R	<17	<6-6	9-12	10-28	145-220	158-236	<5-15	<25	841	<20-20	0.00	8.5	1.4	86.6	0.9
	M	<17	<6	11	17	192	189	~8			<20					
168	n	1	1	1	1	1	1	1	—	—	1	—	—	—	—	—
	R	<17	<6	22	43	256	161	38			<20					
185	n	2	2	2	2	2	2	2	1	1	2	1	1	1	1	1
	R	<17	9-92	17-20	56-67	240-250	299-566	19-26	<25	1394	<20-40	0.09	23.5	2.2	68.5	2.2
	M	<17	51	19	62	245	433	23			~25					
166	n	3	3	3	3	3	3	3	1	1	3	1	1	1	1	1
	R	<17-74	11-1240	<8-28	65-177	217-246	265-498	15-38	26	1018	<20	0.32	19.8	2.4	69.4	4.2
	M	~30	326	13	105	236	310	28			<20					
ST4	n	3	3	3	3	3	3	3	—	1	—	1	1	1	1	1
	R	<17	<6-97	<8-17	14-52	194-238	195-462	10-26		1294		0.10	2.0	2.4	69.0	2.4
	M	<17	40	10	39	218	341	17								
ST3	n	6	6	6	6	5	5	5	—	—	—	—	—	—	—	—
	R	<17-30	16-80	9-31	36-213	240-338	402-541	10-120								
	M	<17	40	22	111	281	477	42								
162	n	3	3	3	3	3	3	3	2	2	3	2	2	2	2	2
	R	<17-20	14-46	10-58	70-95	212-292	318-414	32-64	<25-29	1763-1930	<20	0.12-0.13	16.1-27.3	1.7-5.6	56.7-76.0	2.9-3.5
	M	<17	31	39	80	251	354	50	<25	1847	<20	0.13				2.7

Muddy Limestone and Lower Limestone Shales

Drill hole		Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
179	n	3	3	3	3	3	3	3	2	2	3	2	2	2	2	2
	R	<17-17	15-21	<8-43	<8-52	216-356	329-959	21-117	<25-34	128-699	<20-74	0.17-0.30	26.1-43.0	4.5-6.9	45.1-57.1	3.1-3.6
	M	<17	19	~26	~34	271	549	64	<25	414	~44	0.24				3.4
157A	n	2	2	2	2	2	2	2	1	1	2	1	1	1	1	1
	R	<17-21	20-30	<8-20	77	250-309	350-405	36-82	39	1448	<20-20	0.03	29.6	3.5	58.4	4.2
	M	<17	25	~12	77	280	378	59			<20					
153	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	<17	55	27	199	564	302	229	80	691	56	0.19	48.5	13.9	18.3	2.8

Drill hole		Pb	Zn	Cu	Ni	Ba	Sr	Rb	As	Mn	Hg	S	SiO_2	Al_2O_3	$CaCO_3$	Fe_2O_3
149	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	225	145	64	152	490	337	219	518	854	106	0.13	38.2	10.4	38.5	5.4
152	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	42	48	46	174	986	297	326	175	853	74	0.18	53.3	16.0	14.6	5.1
146		Disseminated mineralization														
72		Mineralized														
107		Mineralized														
121		Mineralized														
126		Mineralized														
155		Minor mineralization														
159	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	24	257	19	32	298	375	33	38	2074	<20	0.18	23.9	12.4	65.3	4.2
182	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	<17	299	31	113	410	435	169	<25	189	120	0.43	45.0	12.3	27.4	6.5
186	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	<17	44	16	41	196	662	24	<25	898	<20	0.06	19.0	2.5	72.8	2.5
187	n	11	11	11	11	11	11	11	2	2	11	2	2	2	2	2
	R	<17-110	30-266	<8-46	23-69	190-1147	237-958	11-289	60-72	226-1190	<20-220	0.50-0.57	12.8-37.3	3.1-11.3	39.1-76.2	1.7-5.0
	M	33	78	19	49	442	630	91	66	708	100	0 54				3.4
168	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	<17	27	39	73	830	89	141	65	3312	<20	0.05	55.1	13.1	2.4	19.2
185	n	2	2	2	2	2	2	1	1	1	2	1	1	1	1	1
	R	<17-34	11-21	<8-17	24-27	232-364	381-440	20	32	672	30-56	0.23	31.3	6.4	54.1	3.2
	M	~21	16	~11	26	298	411				43					
166	n	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	R	37	25	39	91	430	670	198	<25	136	74	0.27	43.2	11.7	29.4	5.2
169	n	4	4	4	4	4	4	4	1	2	4	2	2	2	2	2
	R	<17-24	<6-179	<8-26	<8-63	224-500	426-893	7-105	<25	258-682	<20-60	0.28-0.46	28.1-35.8	7.0-7.3	45.8-53.1	3.0-3.4
	M	≤17	~51	~18	~31	357	573	53		470	~37	0.37				3.2
162	n	2	2	2	2	2	2	2	1	1	2	1	1	1	1	1
	R	~17-18	34-162	19-39	125-163	330-390	445-493	149-176	~25	148	106-112	0.24	5.09	13.5	18.9	6.4
	M	~18	98	28	144	360	469	163			109					

TYNAGH IRON-FORMATION

Iron rich sediments

Major elements analysed by Malcolm Wayt at Ravenscraig (British Steel Corporation) using X-ray fluorescence on samples fused with lithium tetraborate and sodium tetraborate.

Drill hole	sp no.	Depth m	Pb	Zn	Cu	Ni	Ba
96	680	112.5	60	3350	50	50	545
146	671	119.2	145	1035	<20	45	465
152	658	120.1	125	240	30	80	265
149	649	199.8	350	80	55	60	385
"	Schultz		~100	~50	nil	-	~500
159	686	88.7	<40	50	<20	<20	850

Recalculation of Al + Si + Fe = 100%

sp no.	Al	Si	Fe	
680	0.7	52.5	46.8	Dakhla-Oasis (Harder 1964)
671	1.6	37.4	61.0	Lahn-Dill (Harder 1954)
658	2.7	5.6	91.7	
649	0.9	22.6	76.5	
Schultz	1.8	11.2	87.0	Red Sea average (James 1969)
686	0.3	69.3	30.4	Oolitic hematite, Lias, Göttingen (Harder 1951)

Manganese rich sediments

Drill hole	sp no.	Depth m	Pb	Zn	Cu	Ni	Ba	Ti
153	655	223.1	2400	140	35	145	~9000	2360
"	656	228.3	530	1070	40	560	1250	810
"	635	228.9	605	1200	30	730	1250	1520

SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	TiO_2	P_2O_5	CO_2	H_2O-	Total
49.7	0.60	21.45	7.48	0.13	0.44	7.98	0.03	0.14	10.6	0.44	99.1
43.8	1.70	44.90	2.58	0.03	0.42	1.70	0.05	0.14	1.9	0.33	97.6
7.5	3.15	76.36	5.16	0.06	0.78	2.27	0.21	0.11	1.9	0.37	97.9
27.4	1.00	57.77	3.61	0.23	0.35	3.50	0.06	0.11	6.3	0.35	100.7
14.3	2.10	(Total Fe 52.0)		0.30	0.80	3.80	0.08	0.08	–	–	–
65.2	0.25	15.44	3.10	0.10	0.15	5.30	0.02	0.14	9.6	0.35	99.7
15	0.6	41.5	–	0.20	–	1.3	0.07	–	1.1	–	–
46.79	0.25	50.80	0.40	0.01	0.02	0.80	0.05	0.12	0.06	0.08	99.3
2.59	0.75	52.56	0.88	0.11	0.21	22.40	0.1	0.084	18.50	0.21	98.3
39.1	5.7	43.2	–	2.7	1.9	3.7	<0.05	0.4	–	–	100.0
11.51	6.85	29.90	12.08	0.058	1.82	16.97	0.39	1.27	11.97	0.30	93.1

Fe_2O_3	Mn_2O_3
5.7	33.0
1.4	77.6
2.1	79.1

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Structural controls of base metal mineralization in Ireland in relation to continental drift

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Structural controls of base metal mineralization in Ireland in relation to continental drift

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Synopsis

A hypothesis is presented that suggests that both the genesis and the siting of the newly discovered base metal deposits in the Carboniferous rocks of Ireland are controlled by the intersection of north–south upper mantle fissures with east–west to northeast–southwest faults of Caledonian trend. It is proposed that the intrusion of magma at these intersections gave rise to a convective or a partial convective system within the pore waters which leached metals from the Lower Palaeozoic geosynclinal sediments and precipitated them in the overlying Carboniferous rocks or on the Carboniferous sea floor. The formation of the north–south upper mantle fissures parallel to the continental margin is believed to relate to continental rifting in Devonian and Carboniferous times. A similar origin is ascribed to the comparable base metal deposits occurring in the Lower Carboniferous rocks of the Maritime Provinces of Canada.

Concentrated investigation of these intersections may result in further ore discoveries.

Four large base metal deposits have been discovered in Ireland in the past seven years—at Tynagh, Silvermines, Gortdrum and Riofinex at Keel.[2–4a] These discoveries occur in a variety of Lower Carboniferous lithologies. Host rocks comprise sandstones, limestone shales, muddy limestones, dolomites and a carbonate mud bank complex. These low-grade high-tonnage ores contrast with most of the previously worked small sulphide veins elsewhere in Ireland,[5] but show similarities with the strata-bound deposit at Abbeytown mine, County Sligo. The latter has been known for over 100 years and consists of sphalerite and galena disseminations in a Lower Carboniferous calcareous sandstone.[6] The mineral assemblages are typically those of low-temperature hydrothermal origin, but it is important to note the absence of fluorite in association with the ores. Four of the five large-tonnage, low-grade sulphide deposits—Abbeytown, Tynagh, Silvermines and Gortdrum—are distributed along an approximately north–south line.

Known sulphide ore deposits are widely separated, the minimum distance between any two being 18 miles. The extensive occurrence of Lower Carboniferous rocks in the Central Plain presents possibilities for further discoveries, but the boulder clay and peat cover necessarily limits exploration

The juxtaposition of Carboniferous Limestone with older rocks along east–west trending faults is significant in connexion with disseminated sulphide deposits in Ireland. Exploration companies have concentrated their investigations in such areas. Pereira[7] suggested that northeast–southwest sub-mantle fissures govern the distribution of ore deposits in Ireland, and also stressed the importance of the sedimentary environment in Lower Carboniferous times. A hydrothermal origin has been suggested by Derry and co-workers[2] for the Tynagh deposit, which is associated with an east–west fault. Their theory postulated shallow replacement and early infilling of organic structures in a mud bank complex; Schultz,[8] however, favoured a normal hydrothermal origin of later date.

A sedimentary-exhalative theory was proposed by Gordon-Smith[4b] to explain the stratiform Silvermines zinc–lead orebody.

Several points from these theories have been incorporated in a theory of genesis that is capable of explaining the north–south distribution of the ore deposits. This proposes that deposition of minerals in Carboniferous rocks is controlled by the initiation of north–south fissures extending from the upper mantle, and their intersection with faults of Caledonian trend. Geosynclinal deposits underlying the Carboniferous are believed to have provided metals for these deposits. The initiation of continental drift contemporaneously with the formation of structures parallel to the continental margin adds support to the hypothesis.

Geological environment

Structurally, Ireland can be visualized as a large rhomb, with north–south and east–northeast trending sides, situated close to the continental margin. Gravity surveys have shown positive anomalies of the order of 20 mgal associated with the margins of the island.

The important mineralization occurs in the Lower Carboniferous rocks of the Central Plain of Ireland—an area of about 16 000 square miles.

The oldest rocks outcrop in the Ox Mountains and in Donegal in the northwest. They are metamorphic schists and gneisses similar to the Moinian of Scotland. Overlying these rocks are metamorphosed Dalradian geosynclinal sediments which also outcrop in the north and west. Lithologically, these sediments include black pelitic schists with lesser amounts of quartzite, limestone and metadolerite sills and lavas.

Lower Palaeozoic geosynclinal rocks outcrop in the east and west of Ireland and in the inliers of the Central Plain. They include shales, mudstones, silts and greywackes, together with andesitic and acid extrusives and minor intrusives. These rocks are folded, but have suffered only minor metamorphism. Some of the argillaceous rocks have developed slaty cleavage parallel to the axes of folding. The general trend of the axes of folding is sub-parallel to that of the two older groups of rocks; this direction is northeast–southwest in the east, changing to approximately east–west in the west. These Lower Palaeozoic rocks presumably extend under the Central Plain; Murphy[9] suggested a vertical thickness of the order of 10 000 ft for them. Caledonian granite intrusions outcrop in the east, north and west of Ireland.

Old Red Sandstone overlies the Lower Palaeozoic

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rocks with strong unconformity. The thickness is not known in the Central Plain, but is less than 1000 ft on the anticlinal inliers. In the south of Ireland the Upper Old Red Sandstone is often enriched in chalcopyrite and bornite and this is most marked in the Kiltorcan sandstone and conglomerates. Andesitic volcanic activity is

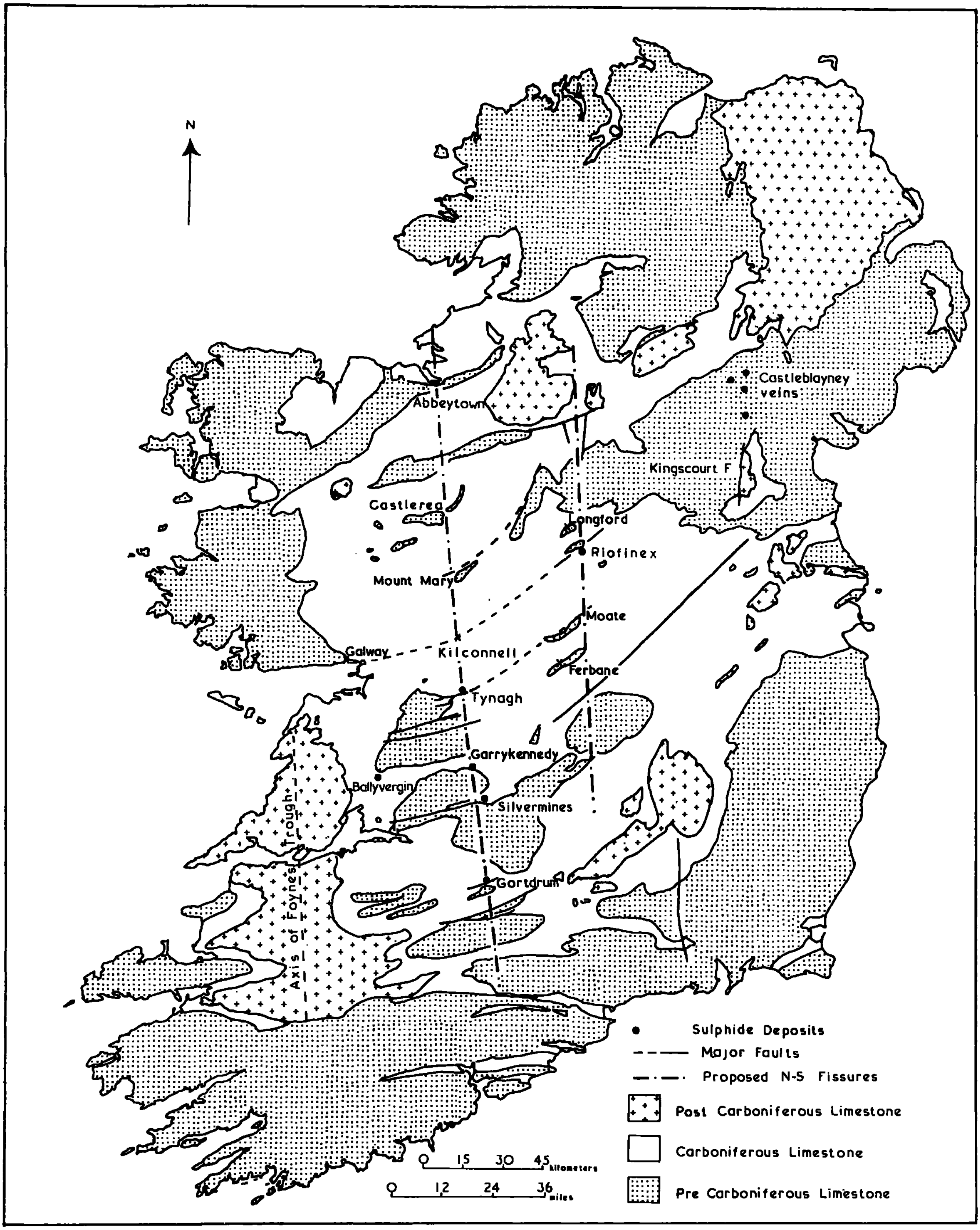

Fig. 1 Geology of Ireland (from the Geological Survey Map of Ireland[44]) with the postulated north–south fissures and faults of Caledonian trend. (Fault running northeast from Garrykennedy, from Murphy[41])

evident in the north and the south, and is similar to the Devonian vulcanicity of Scotland. Charlesworth[10] noted a large number of north–south trending felsite dykes in the northern half of the country.

Carboniferous rocks of shelf-sea facies overlie the Old Red Sandstone conformably, or with slight unconformity, in the southern part of the Central Plain. They consist of limestone, shales and sandstones passing up into bedded muddy limestones and dolomites overlain by a calcareous mud bank complex of upper Tournaisian and lower Viséan age. The Lower Carboniferous Sea transgressed slowly upon the land to the north in upper Tournaisian times and finally covered the northern half of the plain by the early Viséan age. Here the Carboniferous sandstones and limestones of C_1 or C_2S_1 age lie unconformably on Old Red Sandstone and Lower Palaeozoic rocks and, in the northwest, on the Precambrian metamorphic rocks. In the central and eastern districts of this area the diachronous Waulsortian mud bank complex[11] overlies lagoonal limestones of lower Viséan age.

Tuffaceous deposits have been recorded in the Lower Carboniferous rocks of some of the mine areas and may be present throughout the central and southern regions of the plain. The most important lavas and sills occur at Pallas Green, County Limerick, and the feeding vents outcrop to the south along the Gortdrum Fault. The early flows are trachytes, trachyandesites, trachybasalts and olivine basalts of C_2S_1 age. The later igneous rocks of D_1 age also include tuffs and vent agglomerates. These igneous rocks are similar to those of the same age seen in the Midland Valley of Scotland.

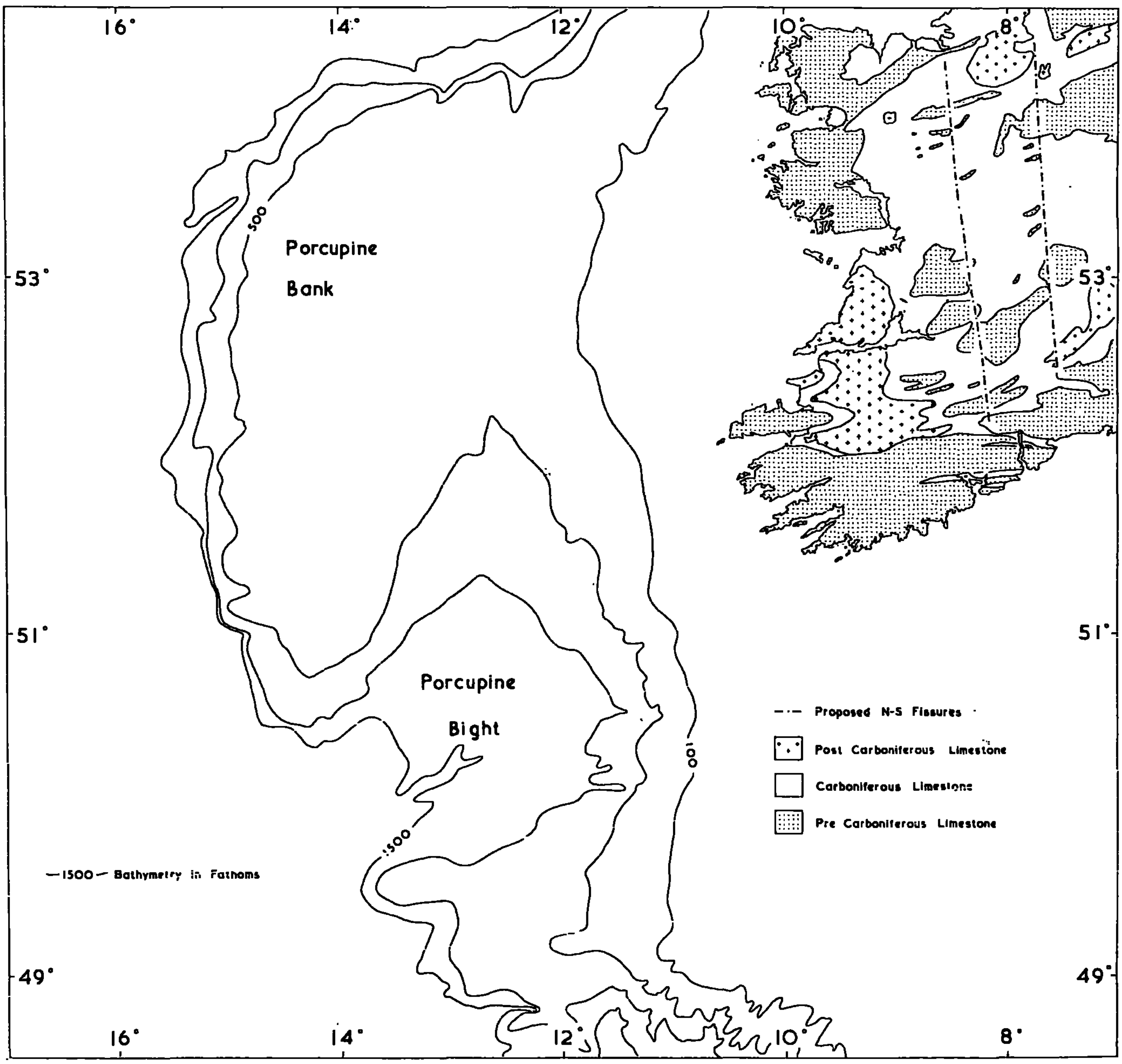

Fig. 2 Submarine topography west of Ireland and its relationship to the geology of Ireland and proposed north–south fissures. (Bathymetry from National Institute of Oceanography Maps, Area 16)

It is possible that east–west faults associated with the base metal deposits were active in Lower Carboniferous times; in support of this Derry and co-workers[2] described some thinning of Lower Carboniferous beds towards the Tynagh fault. There is no stratigraphic evidence to support a theory that the inliers in the Central Plain were large upstanding islands in the Lower Carboniferous Sea, but there may have been some minor emergence. Major movements along the east–west faults were of a later date.

Upper Carboniferous shales, grits and coals occur in County Antrim, County Kilkenny and in the Foynes area to the west. The succession is 3500 ft thick at Foynes and has been deposited in a north–south trending trough (Fig. 1).

Most of the structures in Ireland have previously been related to Caledonian and Armorican earth movements. The Armorican disturbance is envisaged as giving rise to east–west structures in the south and reactivating structures parallel and normal to the Caledonian trends elsewhere. These movements do not adequately explain the many north–south features which include faults, dykes, the predominant joint direction and the Foynes trough.

To the west of Ireland certain major submarine features are also predominantly north–south (Fig. 2): (1) the western edge of the Porcupine Bank; (2) a gravity survey by Gray and Stacey[12] revealed a steep gradient trending north–south associated with the western margin of Porcupine Bank; and (3) the strike of the maximum gravity anomaly off the west coast of Ireland is N 8° W.[12]

The theory of continental drift is now accepted by many geologists. If the validity of this process is assumed, these north–south structures take on a new significance. From the fit of North America and Europe proposed by Fitch[13] the continuation of the Caledonian system is apparent. Westoll[14] believed that the first fractures in the formation of the present North Atlantic Ocean developed between Lower and Middle Old Red Sandstone times. Evidence for this fracturing is provided by the sinistral transcurrent movement of 100 km along the Great Glen Fault, which can be dated as post Lower and pre Middle Old Red Sandstone by stratigraphic means. Such a movement depended upon the opening of a rhombo-chasm, or large rift, between Norway and Greenland. As additional evidence Westoll[14] cited the occurrence of an *Ostracoderm* fauna in a unique development of non-marine sediments of Middle and Upper Devonian age, deposited along the line of the fracture system. This fauna is similar to that of Spitzbergen, but dissimilar to that of the rest of the British Isles. The 30° sinistral rotation of Newfoundland Island during the late Devonian,[15] together with transcurrent movement along the Cabot fault system of similar age,[16] would suggest that there was major movement on both sides of the Atlantic at this time. The splitting of the continents in the North Atlantic region took advantage of Caledonian trends, except in the area west of the British Isles. In this area there appears to have been a crossover from the northwest to the southeast side of the Caledonian orogenic belt (Fig. 3). From the trend of the continental margin west of Ireland the split was apparently north–south. The rifting may have been governed by structures normal to the Caledonian trend, which appears to have swung round to an east–west direction west of Ireland. The split may be the southerly extension of the Greenland–Newfoundland break along the trend of the Ketilides of southwest Greenland[17] (Fig. 3). Structures parallel to this major split were formed during the later Devonian and Carboniferous periods—possibly in response to east–west tension.

Description of base metal deposits

Abbeytown

At Abbeytown mine sphalerite, galena and pyrite are disseminated in, and replace, a calcareous sandstone 24 ft thick.[6] They also partially replace the limestone above and below this sandstone. The limestones are dolomitized in the vicinity of the ore. The sandstone may be equivalent to the Mullaghmore Sandstone of S_2 age[18] which outcrops to the northeast. The ore deposit lies between two east–west faults which have brought the Carboniferous Limestone against schists of Moinian type. These same schists presumably underlie the limestone.

Tynagh

At Tynagh mine fine-grained pyrite, galena, sphalerite and some chalcopyrite, often intimately mixed with barytes, replace and infill a Waulsortian mud bank complex of C_1 to C_2S_1 age. The complex lies adjacent to an east–west fault, with a throw of 1200 ft to the north which brings Old Red Sandstone against the ore deposit. A bedded iron formation,[19] associated with tuffs, lies to the north of the sulphide deposit at the same stratigraphic horizon. Schultz[19] suggested that this iron deposit was derived by intensive chemical weathering of lower Dinantian sediments that had been exposed on newly emergent land. Derry and co-workers,[2] however, regarded the ore deposit as a precipitate from metal-bearing solutions, possibly arising along the east–west fault and seeping into an area of recent organic growth of the mud bank complex. The silica, manganese and much of the iron, however, remained in solution and were deposited in a protected basin off the reef. The green tuff bands interbedded with the iron ore point to simultaneous local volcanic activity. The banded and colloform texture of the sulphide suggest either penecontemporaneous deposition or early diagenetic replacement with or within the mud bank complex. The thinning of some of the Carboniferous formations towards the fault led Derry and co-workers[2] to conclude that movement continued throughout ore deposition.

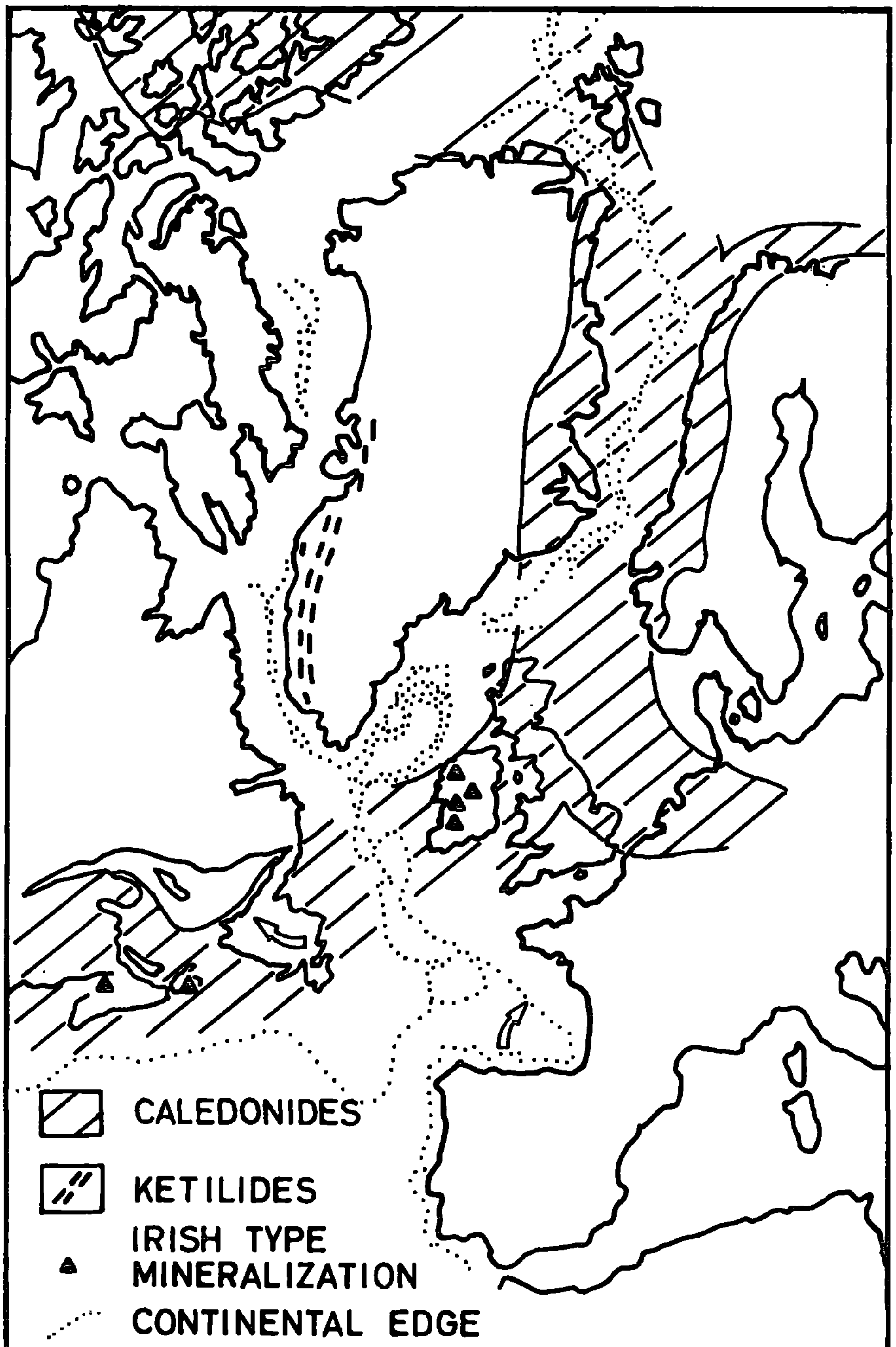

Fig. 3 Reconstruction of the North Atlantic continents before drift (after Fitch[13]) illustrating relationship of Irish-type mineralization to the continental margins and the Caledonian geosynclinal rocks. (Ketilides from Dearnley[17])

Silvermines

The Silvermines deposit[1] consists of galena, sphalerite, pyrite and barytes extending 2 miles along a complex east–west fault and associated east–northeast and north–south trending faults. Ore is also seen as disseminations in the lower dolomite of Tournaisian age. The ore is rich in silver, containing between 6 and 80 oz/ton. The fault has a throw of between 800 and 1100 ft to the north and brings Old Red Sandstones, overlying Silurian shales, in contact with the Carboniferous limestones. The largest deposit, however, is the newly discovered zinc–lead *G* orebody to the north of the fault. This is a stratiform deposit lying between a muddy reef limestone and the overlying dolomite breccia of lower Viséan age. A large strata-bound deposit of cryptocrystalline barytes occurs at the same horizon just to the east at Ballynoe mine. Gordon-Smith[4b] suggested that the *G* orebody and the barytes deposit result from sedimentary precipitation of sulphides and sulphates at different redox potentials—the barytes in oxidizing conditions and sulphides in a shallow basin with reducing conditions. The metal-bearing solutions may have emanated from the east–west fault. Colloform and sedimentary structures are common in the *G* orebody. The only evidence for volcanic activity is the footwall shale, which may be a tuff band.

Gortdrum

Bornite, tetrahedrite and chalcopyrite occur as replacements and fracture fillings in Tournaisian muddy limestones and limestone shales to the north of a fault throwing Old Red Sandstone against Carboniferous limestones.[3,4a]

This replacement deposit is associated with feldspar–quartz porphyry dykes. Four intrusions, two of which are probably volcanic necks, outcrop further west along the same fault and also comprise feldspar–quartz porphyry. The volcanic necks are the feeders for the Pallas Green volcanic series of lower Viséan age. A consideration of the spatial relationship between the ore and the intrusions implies a lower Viséan age for this deposit.

Veins containing galena, sphalerite and barytes occur at Oola Hills, half a mile north of Gortdrum. A lead–zinc deposit at Carrickittle, 5 miles to the west of Gortdrum mine, occurs in the Waulsortian Limestone and is also associated with a quartz–feldspar porphyry intrusion. This apparent zonation of a copper deposit surrounded by lead–zinc deposits may have been repeated vertically, though the evidence has been removed by erosion.

Riofinex

Galena, sphalerite, pyrite and barytes occur in Silurian banded grits and mudstones, Devonian sandstone and conglomerates and the Tournaisian silts, limestones and shales.[3,4a] The massive and disseminated mineralization is associated with an east–west fault which brings Silurian rocks overlain by Old Red Sandstone against sandstones and limestones of Lower Carboniferous age.

General features of Irish ore deposits

The low-grade high-tonnage ore deposits in Ireland consist of a low-temperature suite of sulphides; sphalerite, galena, pyrite and, less commonly, copper sulphides, often accompanied by barytes. Wallrocks are dolomitized in some cases, although dolomitization is not necessarily accompanied by mineralization. Silver of the order of 2 oz/ton of ore is present in most of the deposits, although it is appreciably higher in the vein deposits of Silvermines. Usually, the sulphides are fine-grained and often intimately mixed. Sphalerite, galena and pyrite exhibit colloform textures in some deposits.

There is no evidence to suggest one source of ore at depth for all the deposits—rather, the zoning within some of the mines, for example Tynagh and Gortdrum, points to an individual source for each area of mineralization. Igneous activity in the form of tuff bands is evident in some of the deposits and in the south the sulphides are intimately associated with feldspar–quartz porphyry intrusions. Approximately east–west trending faults which bring Old Red Sandstone or older rocks into contact with Carboniferous Limestone are a feature of each deposit. These faults are parallel to the axes of Caledonian folding. Movements along some of these faults during the Lower Carboniferous can be demonstrated.

The evidence at Tynagh, Silvermines and Gortdrum points to a period of major mineralization during late Tournaisian and early Viséan times. This coincides with the time of major igneous activity in the Carboniferous in which basic and intermediate lavas were extruded.

Lead isotope studies on these Irish ores by Moorbath[20] and Pockley[21] gave age dates concentrating in the Carboniferous, but the limited precision of these results (from ±40 to ±90 m.y.) renders them of little value in the present context.

Abbeytown, Tynagh, Silvermines and Gortdrum mines are distributed along an approximately north–south line, subsequently referred to as the 'Abbeytown–Gortdrum line'. The trend is N 7° W (Fig. 1). The Silvermines and Abbeytown deposits occur in Carboniferous rocks faulted against large inliers of older rocks. Tynagh and Gortdrum deposits are associated with small Old Red Sandstone inliers. Adjacent to this line are Old Red Sandstone and Lower Carboniferous Sandstone inliers at Mount Mary and Castlerea. The Riofinex deposit is also spatially related to an Old Red Sandstone inlier. A line drawn approximately parallel to the Abbeytown–Gortdrum line through the Riofinex deposit and adjacent to the eastern extremities of three other Old Red and Carboniferous Sandstone inliers near Longford, Moate and Ferbane, runs N 3° W and is referred to subsequently as the 'Riofinex–Ferbane line' (Fig. 1).

The major structural directions, except in the extreme south of Ireland, are Caledonian and north–south. The distribution of major sulphide deposits appears to be governed by these same trends.

Smaller sulphide deposits in eastern Ireland also exhibit a north–south distribution: this is especially obvious in the Castleblayney area (Fig. 1), where epigenetic vein mineralization in Silurian rocks occurs on the possible northerly extension of the Kingscourt Fault. Veins containing sulphides in the Ballyvergin area, County Clare,[5] also have a north–south trend. According to Murphy,[22] late north–south fractures at Avoca mine, County Wicklow (a conformable copper–lead–zinc and iron sulphide deposit in Ordovician rocks), contain enough remobilized chalcopyrite to make small-scale stoping worth while.

Deposits similar to the Irish type occur in the Maritime Provinces of eastern Canada, the largest being at Walton, Nova Scotia. In this area rocks underlying the

Carboniferous are slates, argillites and quartzites of the Meguma Series, of Lower Palaeozoic age. Lower Carboniferous sandstone, shales, ferruginous limestones and conglomerates of the Horton and Cheverie Formations lie with strong unconformity on the Meguma Series. Boyle[23] noted the generally high sulphur, lead, zinc, copper and barium contents of the Horton–Cheverie group. According to Bell,[24] these rocks are equivalent to the limestones, shales and sandstones of Tournaisian age in Ireland. Fissile limestones, limestone conglomerates, and shales of the Windsor Group, which correspond to the Viséan rocks of Ireland, overlie the Horton–Cheverie Formations.

The barium–lead–zinc–silver deposit at Walton consists of fine-grained sphalerite and galena overlain by cryptocrystalline barytes. It is approximately stratiform and was formed by replacement and fracture filling of the lower Windsor limestones and the underlying Cheverie sandstones and shales.[23] The deposit is localized in a brecciated zone at the intersection of two major fault zones. The directions of these faults are east–west and northeast–southwest. The age of mineralization is unknown, but the stratigraphic and structural location of the deposit is similar to that of the Irish deposits.

The large-tonnage Irish deposits contrast strongly with the lead–zinc deposits of the English northern Pennines.[25] The main differences between the two are shown in Table 1. The occurrence of sulphide deposits at the junction between the inner fluorite zone and outer barytes zone in the Pennines suggests that sulphide deposition only occurred after removal of a substantial proportion of the fluorine from the ore solutions. There was an estimated 20 000 000 tons of fluorite in the north Pennine ore field. The Pennine deposits are similar to those of the Erzgebirge,[26] where the source of mineralization is related to Hercynian granites and the fluorite zone is again well developed.

Table 1 Comparison of Irish and north Pennine mineralization

Characteristics	Irish deposits	North Pennine deposits
Host rocks	Carboniferous sandstone, limestone shales, muddy limestones, Waulsortian reef	Carboniferous sandstone, shales and limestones
Basement	Folded geosynclinal rocks	Older granite
Age	Lower Carboniferous?	Hercynian? (Moorbath[20])
Attitude	Conformable and irregular	Veins and flats
Grain size	Fine	Coarse
Principal metal sulphides	Pb, Zn, Fe, Cu	Pb, Zn (Fe, Cu)
Principal gangue minerals	Barytes	Barytes, fluorite and ankerite
Structural control	Associated with widely separated east–west faults of large throw	Many faults of small throw
Type	Low-grade, high-tonnage	High-grade, low-tonnage
Zonation	Poor	Marked
Areal extent of mineralization from one source	Restricted	Large

Fluorine is known to concentrate in the later-stage differentiates of nepheline syenites and granites and hence is involved in metasomatism and in vein mineralization related to the crystallization of the final phase of this type of magma. The absence of fluorite in the large base metal deposits in Ireland puts a magmatic hydrothermal source theory for these sulphides in some doubt.

Another possible source of the metals in the deposits is the trace concentrations in the underlying Lower Palaeozoic geosynclinal rocks. The possibility that trace quantities of metals in rocks may be dissolved by circulating thermal waters and eventually precipitated in a favourable environment for deposition is gaining in popularity. Petrascheck[27] believes that the lead, zinc and manganese deposits on each side of the Red Sea may be best explained by secondary hydrothermal derivation of metals from deeper levels.

Work on the Salton Sea brine well waters[28] is especially relevant in this respect. These brines contain high concentrations of lead, zinc, barium, iron and manganese and, according to oxygen and hydrogen isotope studies by Craig,[29] are meteoric in origin. A radiogenic tracer study[30] of lead and strontium in these deep thermal brines indicated that 80–100 per cent of the strontium and 50–100 per cent of the lead were acquired from sediments underlying the Salton Sea. The investigation also shows that the magma that formed the local rhyolites could not be the source of the lead. The large geothermal anomaly in the area suggests that a magma chamber may exist at depth.

Theory of genesis of Irish ore deposits

During Lower Carboniferous times approximately north–south fissures were formed in response to incipient continental splitting. At least two of these fissures underlie Ireland—the Abbeytown–Gortdrum and the Riofinex–Ferbane fissures. The continuity of these fissures suggests they extend from the upper mantle. The fissures intersected east–west to northeast–southwest faults formed or reactivated by early Armorican movements. Magma rose along these fractures reaching a high level in the crust at the fracture intersections and along east–west fractures in the south, where the early Armorican movements were more intense. At times some of the magma reached the surface. These volcanics and intrusives were basic and intermediate in type. Intrusions centred on the intersections acted as 'hot spots' giving rise to a convective or partial convective system within pore waters in the Lower Palaeozoic geosynclinal rocks. Heat was maintained by the addition of juvenile water from the magma and by continued magmatic activity. Water, containing base metals dissolved from clay particles, organic matter and fine authigenic sulphide while permeating through the Lower Palaeozoic rocks, rose along the fracture intersections and to some extent along the east–west faults. The precipitation of metals from this water was dependent upon a variety of factors, including release of pressure, lowering of temperature and the reactivity of wallrocks. Thus although the intersections governed the passage of the rising fluids, the resultant ores occur as replacement or sedimentary deposits close to, but not necessarily directly above, the intersections.

Similar fractures parallel to the continental margin are present in the Maritime Provinces of Canada. Replacement deposits are found in association with these fractures in overlying Lower Carboniferous rocks. In this western counterpart of the Irish base metal province the comparatively small extent of Lower Carboniferous rocks accounts for the infrequent occurrence of sulphide deposits of this type. Where the basement consists of relatively impermeable metamorphosed rocks poor in adsorbed ions, the deposits will be small.

The coincidence in time of earth movements, and the occurrence of similar types of mineral deposits within the same stratigraphic horizon and comparable structural conditions on either side of the Atlantic, is consistent with the hypothesis that these ores were generated as a consequence of the process of continental drift.

Geochemical considerations

Experimental work, accompanied by thermodynamic calculations by Helgeson,[31] demonstrates that base metals may form water-soluble chloride complexes. Barnes and Czamanske[32] believe that metals may also enter solution as sulphide and bisulphide complexes at least up to a temperature of 250°C.

The source of the solutions giving rise to Irish mineralization is believed to be broadly similar to that of the Salton Sea area. In this case the underlying rocks are mainly Lower Palaeozoic geosynclinal rocks. To establish the concentration of metals in these rocks 63 samples of Ordovician and Silurian sediments and volcanics were collected throughout Ireland, away from known mineralized areas, and analysed with a Philips X-ray fluorescence spectrograph, PW 1540. The results of these analyses are presented in Table 2, with precision data and analyses of the standard rocks G_1 and W_1. The standard deviations from the mean values are high and the results of this reconnaissance survey demonstrate only the general order of magnitude of trace elements in these rocks. Silver was not determined, but Taylor[33] quoted a Clarke value in greywackes and shales of 0·05 ppm and a similar value is assumed for these sediments. Greywackes and silts constitute the bulk of the Lower Palaeozoic rocks in Ireland.

Table 2 Minor-element concentrations in some Lower Palaeozoic rocks from Ireland (parts per million)

34 samples of shales and greywackes				
	Pb	**Zn**	**Cu**	**Ba**
Range	<17–71	8–288	<8–82	111–1270
Mean	22	109	51	697
Standard deviation	±16	±53	±19	±58
Experimental precision on ten replicate determinations				
Mean	20	105	57	720
Standard deviation	±4	±2	±4	±27
Relative deviation	20%	2·2%	7·0%	3·8%
29 samples of volcanics and intrusives				
	Pb	**Zn**	**Cu**	
Range	<15–62	5–130	<5–82	
Mean	~18	69	24	
Standard deviation	±14	±42	±22	
Experimental precision on ten replicate determinations				
Mean	33	18	5	
Standard deviation	±4	±2	±2	
Relative deviation	12·4%	9·8%	38%	
G_1 analyses	51	52	17	
G_1 recommended (Fleischer[43])	49	45	13	
W_1 analyses	~7	82	124	
W_1 recommended (Fleischer[43])	8	82	110	
Order of magnitude of concentration, presuming that the sediments make up 80% of the Lower Palaeozoic rocks				
	Pb	**Zn**	**Cu**	**Ba**
	20	100	45	(700)

The high thermal gradient caused by magmatic intrusion would initiate movements of pore waters towards the convective upcurrent. This movement would take advantage of cleavages in the argillites and silts and of porous and permeable sediments. The volume of Lower Palaeozoic rocks contributing metal would be elongate in the Caledonian fold direction and more narrow normal to the axis of folding. Two models consistent with these considerations are presented. Both assume uniform leaching in parallelepipeds of vertical thickness 1 mile. The top of these source volumes lie about 1000 ft below the Old Red Sandstone–Lower Palaeozoic unconformity.

The first is 10 miles long in the direction of the Caledonian axis and 6 miles wide. The vertical axis of this model corresponds to the intersections of the north–south fissures with the faults of Caledonian trend. The ends and sides of this figure are thus, respectively, 5 and 3 miles from the intersection at the shortest point. Assuming orders of magnitude for lead, zinc, copper and barium in Table 2, the following expressions may be used to calculate the percentage of each element required to form an ore deposit.

$$F = \frac{\text{wt of metal in ore deposit}}{\text{wt of source rock}}$$

Hence F is the proportion of source rock required to form the ore deposit; then the percentage of metal leached from the source volume $= \frac{F}{C} \times 100$, where C = concentration of metal in source rocks. The proportion of the lead required to form the Tynagh ore deposit may be calculated as follows.

Wt of lead in ore deposit = 600 000 tons (Table 3)
Wt of source rock = $6 \cdot 72 \times 10^{11}$ tons, calculated from a source volume 10 miles × 6 miles × 1 mile with specific gravity of 2·73 (Murphy[9])
$F = 6 \times 10^5/6 \cdot 72 \times 10^{11} = 0 \cdot 89$ ppm
Amount of lead in source rock = 20 ppm (Table 2)
Percentage of lead required for ore deposit
$= 0 \cdot 89/20 \times 100 = 4 \cdot 5\%$

Estimates of weights of various metals are presented in Table 3; they are approximations calculated from published reserves and mined ore and will therefore be underestimates of metal contributed by the upwelling solutions. Assuming the validity of this model, the formation of the Tynagh deposit involves the solution of 4·5 per cent by weight of the total quantity of lead in the source volume, as shown above, 1·8 per cent of the silver, 0·74 per cent of the zinc, 0·17 per cent of the copper and 0·42 per cent of the barium.

Table 3 Approximate tonnages of elements in various mineral deposits

Deposit	Pb	Zn	Cu	Ag	Ba
Abbeytown	50 000	50 000			
Tynagh	600 000	500 000	50 000	600	2 000 000
Silvermines	500 000	1 000 000	—	500	?
Gortdrum	—	—	60 000	90	—

The second model has the same general shape, but a length of 6 miles and a width of 4 miles. The formation of the Tynagh deposit for this source volume of Lower Palaeozoic rocks would require leaching of 11·2 per cent of the total lead, 4·4 per cent of the silver, 1·86 per cent of the zinc, 0·42 per cent of the copper and 1·06 per cent of the barium. The Silvermines deposit has approximately twice as much zinc as the Tynagh deposit and, consequently, the quantity of zinc leached increases by a similar factor. More barium is probably needed to satisfy the Ballynoe barytes deposit. The Gortdrum deposit requires the solution of 0·20 per cent of the copper assuming the first model and 0·51 per cent for the second; the absence of lead and zinc is due to zonation of sulphides in the area. The Abbeytown lead–zinc deposit is small because of the low permeability and reactivity of the underlying quartz–mica schist and gneiss.

The factors governing the solution of these metals are their availability and solubility as complexes. Some of the lead, zinc, copper and silver may be present in authigenic and diagenetic sulphides. Barnes and Czamanske,[32] working on sulphide and bisulphide complexing, have shown that zinc, copper and lead are all soluble in hot waters as bisulphide complexes. These same elements may also be associated with clays and organic matter. The ionic radii and electronegativity of lead (Pb^{++}, $r = 1 \cdot 20$ Å and $e = 1 \cdot 55$) and silver (Ag^+, $r = 1 \cdot 26$ Å and $e = 1 \cdot 42$) preclude their incorporation into octahedral or tetrahedral sites in clay mineral structures. Any lead and silver not in the sulphide phase may be adsorbed on the clays and organic matter and is thereby readily available to percolating water. The ionic radius and electronegativity of zinc are the same as those of the ferrous ion ($r = 0 \cdot 74$ Å and $e = 1 \cdot 66$); the zinc is therefore camouflaged by the ferrous ion in clay mineral structures. Barium can substitute for potassium in potash feldspar and is strongly absorbed into intersheet positions in clay minerals. Barium is sparingly soluble as a sulphide which hydrolyses to a mixture of the hydroxide and hydrosulphide.

The general statements made above go some way towards explaining the preferential solution of lead and silver compared to zinc. The zinc in the clay lattice will only be released on the breakdown of the clay mineral.

Green[45] found the contents of fluorine in sandstones and shales to be 290 and 590 ppm respectively. This fluorine substitutes for (OH) groups in phyllosilicates and is therefore not readily available for solution.

The Salton Sea brines are different from the thermal waters envisaged in relation to Irish mineralization. The temperatures at the bottom of the 5000-ft well in the Salton Sea area were reported[34] as being between 300 and 350°C. At this depth the sedimentary rocks are metamorphosed to the low green schist facies. This metamorphism may explain the high zinc to lead ratio in the brines. Analyses of reservoir brines from two wells[34] gave the significant concentrations, in ppm, as lead, 84 and 80; zinc, 790 and 500; barium, 235 and 250; silver, 0·8 and 2; copper, 8 and 3; and fluorine, 15 and not reported. In Ireland the temperatures of the waters are thought to have been lower and the metals were derived by leaching, although the maximum amount of leaching probably took place along major fractures and over the intrusion.

The results and considerations of the geochemistry discussed above support the theory that the metals in Irish deposits were derived from the Lower Palaeozoic basement. The actual source volume, the shape of this volume and the degree of leaching will be different in different cases. An additional factor may be the high heat flow to be expected in continental margins in times of incipient drift. This heat flow may have driven water out of sediments at deeper levels than considered here.

Boyle[23] has noted high trace-element concentrations of lead, zinc, copper and silver in the grits, arkoses, shales and sandstones of the Tournaisian Horton and

Cheverie Formations of Nova Scotia, and suggested that the mineral deposits were formed by concentration of these trace elements. In southern Ireland the Upper Old Red Sandstone is rich in copper. The explanation favoured by the writer is that these metals were deposited as sulphides from mineralizing solutions originating in the convective system. Part of the upward current could escape through porous sandstones, slowly precipitating sulphides. Interaction with groundwaters may have accelerated the process.

Comparison of North Atlantic rifting with the Red Sea Graben

Westoll[14] compared the incipient drift in the North Atlantic area in Devonian–Carboniferous times with the Red Sea area today. The Red Sea Graben is envisaged as being analogous to the Greenland–Norway rhombochasm, while the transcurrent faulting involving sinistral movement of 100 km along the Jordan Rift Valley[35] is similar to movement along the Great Glen Fault. The Oligocene olivine basalt lavas in this area also compare with the Carboniferous lavas of the Midland Valley of Scotland. The analogy continues with the occurrence of deposits of lead, zinc, iron and manganese minerals on either side of the Red Sea. Deposits between El Qosieir and Bir El Ranga in Egypt[36] occur mainly as lenticular bodies in metasomatized basal Miocene limey grits. They have a linear distribution adjacent and parallel to the Red Sea Graben. Gindy[37] has shown that the high uranium content of these deposits could not have been derived from Tertiary basalts. He suggested that the labile uranium was leached from the Precambrian rocks and overlying sediments by uprising fluids, believing that other metal ions were remobilized in this manner and precipitated in reactive lower Miocene rocks. The syngenetic zinc and iron sulphides, associated with hot brines, discovered recently in the Red Sea,[38] may also have been derived from underlying sediments. Here the existence of basic intrusives has been proved by Drake and Girdler.[39] According to hydrogen and oxygen isotope work by Craig,[29] the waters are of meteoric origin. The intrusives may have been responsible for initiating a convective system in these brines.

The Irish base metal deposits are envisaged as having a similar genesis to the Red Sea deposits. Their formation was also connected with the formation of a continental split, but their deposition has occurred further from the rift than the Red Sea ores. The Irish deposits are related to structures removed from the original rift by approximately 270 miles. Parallel mineralized structures at this distance from the Red Sea are not known.

Any deposits close to the centre of rifting in the North Atlantic, as is the mineralization near the Red Sea (and the mineralizing fluids of the Salton Sea, another area of embryonic drift), now lie on the edge of the continental shelves or, more probably, have been removed by erosion.

Economic considerations of the hypotheses

The occurrence of sulphide ore deposits in Ireland, either as epigenetic or syngenetic bodies, is not significant in respect to the origin of the mineralizing solutions. The metal-bearing waters arose along the intersection of north–south fissures with faults of Caledonian trend. Precipitation of sulphides depends on various factors, and exploration programmes should take account of all possible depositional environments. The ores can occur in sandstones as well as limestones, and syngenetic deposits may occur at some distance from the intersection. Further syngenetic deposits may yet be found in the proximity of known epigenetic deposits.

Exploration programmes should concentrate on intersections of faults of Caledonian trend with the postulated north–south fissures: two of these fissures are the Abbeytown–Gortdrum line and the Riofinex–Ferbane line. The newly discovered mineralization at Moate[40] lies on the Riofinex–Ferbane line, and was predictable by this hypothesis. Arcuate east–west to east–northeast faults are particularly continuous in Ireland. Murphy[41] proved a length of 80 miles for a fault running northeast from near Garrykennedy (Fig. 1). Other faults of Caledonian trend may be related to Old Red Sandstone inliers. Possible intersections are marked in Fig. 1; two intersections require fuller explanation. At Garrykennedy, on the southeast shore of Lough Derg in County Tipperary, galena occurs in veinlets on an east–west fault in Silurian silts.[5] Carboniferous Limestone outcrops a mile to the north on the opposite shore of the lake and also 1 mile to the east, and is presumably present on the lake bottom. In this context it is important to note that Silurian rocks adjacent to the Silvermines and Riofinex ore deposits are also mineralized. This mineralization may represent the roots of the sulphide deposits brought to the surface by subsequent movement along the east–west faults. The Garrykennedy lead showings lie on the Abbeytown–Gortdrum line and it is possible that a base metal deposit lies just north of Garrykennedy on the lake bottom. It may be that a deposit here would have been partially eroded by ice or river action in Pleistocene and Recent times.

The second area is at Kilconnell, County Galway, 8 miles west of Ballinasloe. The southerly shoreline of the Galway granite is straight at N 84° E. There is no gravity contrast across this line, but the writer believes this feature is a fault with downthrow to the south. If granite is faulted against granite no density contrast would be expected. The direction of the shoreline is parallel to faults in the south of the Galway granite and to other faults in western Ireland. An arcuate fault, subparallel with other faults of Caledonian trend and having a downthrow to the south, would extend eastwards from the Galway granite fault and intersect the Abbeytown–Gortdrum line 8 miles west of Ballinasloe. The extrapolation of this fault direction takes it to Riofinex, Keel, where a mineralized fault with southerly throw is known. There is no outcrop of Old Red Sandstone at Kilconnell, so any deposit may be deep, but it is significant that a younger limestone outcrops to the south of this postulated fault line.

The possibility that the Kingscourt Fault is a surface manifestation of a north–south fissure is worthy of investigation. The Castleblayney lead–zinc veins may lie on the northerly extension of this fault, as was mentioned previously. The Ballyvergin sulphide deposits[42] may also relate to a north–south fissure.

Sulphide deposits may be more frequent but smaller in the south, as a result of closer spacing of east–west faults near the Armorican front.

Acknowledgement

The writer wishes to record his thanks to Dr. K. C. Dunham for introducing him to this extremely interesting ore field and to Dr. R. L. Stanton, who initiated his interest in ore deposits. He is particularly grateful to Mr. A. P. Stacey for stimulating discussions on the geophysics and structure of the North Atlantic region, and is indebted to Dr. D. M. Hirst for encouragement, advice and suggestions and to Mr. R. Phillips for a critical reading of the manuscript. Finally, he would like to express his appreciation to the National Environment Research Council for financial support in the form of an industrial fellowship.

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Discussions and contributions

Structural controls of base metal mineralization in Ireland in relation to continental drift

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Structural controls of base metal mineralization in Ireland in relation to continental drift

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Further contributed remarks and author's reply to discussion* on paper published in *Transactions/Section B (Applied earth science)*, vol. 77, August, 1968, pp. B117–28

A. S. Burgess† With reference to the paper by Russell, I should like to attempt to define the existence of geofractures on a mechanical basis.

On examination of Russell's concept of regularly spaced geofractures extending through the crust, the equivalence to jointing in a sedimentary rock is most striking. Empirical relationships between thickness and lithology and joint frequency have been recognized, and the models of Price[1] and Hobbs[2] have put them on a theoretical basis. Adopting the former of these, the essentially brittle region of the crust is equivalent to the competent bed, and the more ductile layer to the underlying bed, which prevents complete opening of the joint.

At depth, hydrostatic stress conditions (σ_z) equal to the weight of overburden exist owing to long-term creep effects. Deformation and failure, however, must be based on effective stresses, defined by Terzaghi and Peck[3] as

$$\sigma' = \sigma - \mu$$

where σ' is the effective stress, σ the total stress, and μ the pore pressure due to fluids. The existence of high pore pressures within rocks has been advanced by Hubbert and Rubey[4] to explain overthrusting, and recent experimental work by Brace and Martin[5] has established the concept as applicable even for crystalline silicates.

If the effective hydrostatic stress, σ_z', is reduced in a lateral direction so as to induce failure, then if $\sigma_z' >$ uniaxial compressive strength, S_c, of the material, normal fault compressive failure will

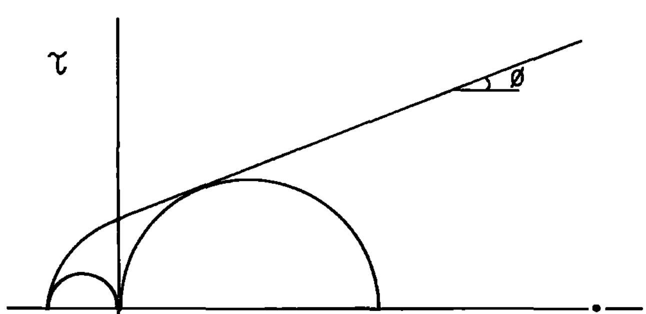

Fig. 1 Diagrammatic Mohr failure envelope for rock

result (Fig. 1). But if $\sigma_z' < S_c$, then tensile failure with the plane of rupture perpendicular to the minor principal stress will be produced.

If the brittle layer is everywhere under stress such that it is on the point of failure, then, after the initial fracture, further fractures will occur at separations governed by the magnitude of shear stress generated in the brittle-to-ductile zone due to plastic failure, and analogous to the restraining frictional shear stress generated along bedding planes in sedimentary rocks (reference 1, p. 145). Thus a regular spacing of geofractures would be expected, the frequency being determined by the pore pressures and the strength characteristics of the material.

The conditions necessary for these geofractures would be realized under east–west tension due to drift, as Russell has suggested.

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Author's reply

M. J. Russell I would like to thank the contributors to the discussion for their interest and criticisms. The comments by Mr. A. S. Burgess help to resolve some of the problems of the paper and allow a refinement of the hypothesis. The suggestion that the geofractures are joints on a very large scale permits the 50- to 60-km interval between them to be viewed as a minimum joint frequency, which may be useful in the prediction of the approximate positions of other geofractures. Burgess considers high pore pressures to be critical in the formation of vertical fissures within a tensional regime. If the pore pressures are too low, then normal fault compressive failure results. If we assume this role for pore pressures in Ireland, then the Abbeytown–Gortdrum line and the Keel (Riofinex)–Ferbane line (1 and 2, respectively, in Fig. 2) are vertical fissures in the brittle crust formed as a consequence of east–west tension and high pore pressures. The geofracture that comprises the Kingscourt Fault (3 in Fig. 2) exhibits normal fault characteristics formed in the same distensional zone but where the pore pressures were low.

High pore pressures are to be expected in zones of rifting. From a consideration of the quantity of organic carbon in Phanerozoic sedimentary rocks of the U.S.S.R.[1] and America, Nicholls[2] has demonstrated maximum degassing of the mantle to have taken place 350 m.y. ago—a time that corresponds well with the age of initial rifting of the North Atlantic region suggested here.

There is, as yet, no direct evidence bearing on the origin of the mineralizing solutions, but degassing of the mantle could transfer heat either directly or via the formation of magma from the partial melting of rocks in the deep crust, as envisaged by Bailey,[3] and thereby induce a convective system in the pore waters of the upper crust.

The age of the first rifting in the North Atlantic is still controversial. From a consideration of the movements along the Great Glen[4] and Cabot[5] Faults, Webb[6] concluded that the original rift was formed in Devonian–Carboniferous times. Sheridan and Drake[7] concurred with that, demonstrating that the Acadian disturbance does not extend to the northeast margin of the Newfoundland shelf. Also, this orogeny does not continue into Ireland; neither does the Hercynian orogeny affect Newfoundland. Heirtzler and Hayes[8] have suggested that the magnetic quiet zone on both sides of the North Atlantic represents ocean-floor spreading during the long period of no reversals in magnetic polarity that occurred in the late Palaeozoic era.

Dr. J. A. E. Allum suggested (pp. B44–5) that the hypotheses presented by the writer should be kept separate from the theory of continental drift. Recent geophysical evidence for ocean-floor spreading[9] and the theory of plate tectonics[10,11,12] strongly support drift theory. This might suggest that it would be increasingly useful for geologists to think in terms of a paradigm, that is, the paradigm of continental drift. The concern is not narrowly to verify continental drift theory but rather to advocate the usefulness of the theory substantively in research. Inasmuch as research continues to demonstrate the efficacy of the paradigm, continental drift remains verifiable. In this particular case the generation of a theory of Irish mineralization was partly grounded in various predispositions held by the author (and these included a predisposition for the paradigm as such) and, just as important, in the realization that Ireland is close to a 'docile' continental margin. Dewey has also recently demonstrated the advantage of

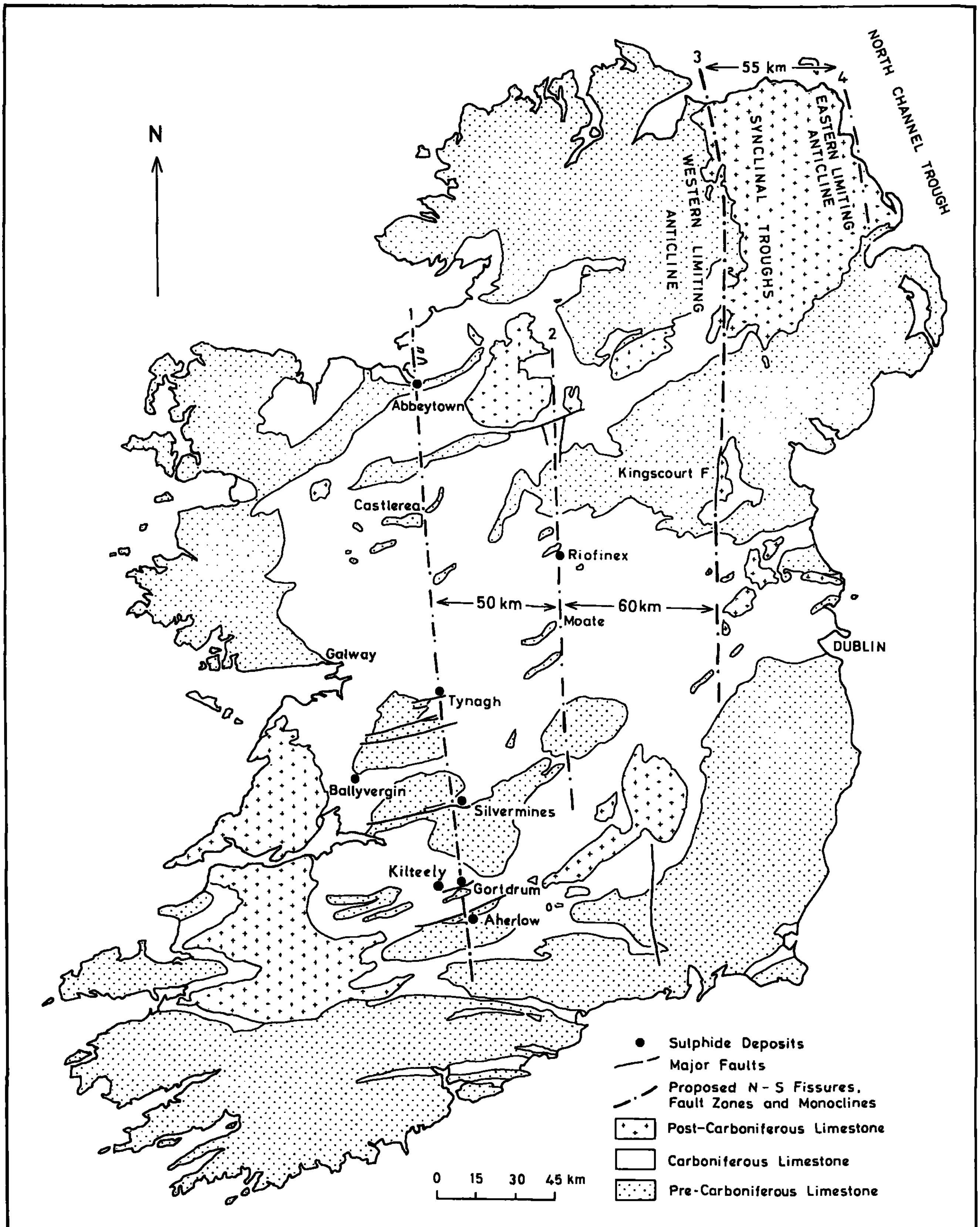

Fig. 2 Geology of Ireland (from the Geological Survey map of Ireland[37]) with postulated north–south geofractures and the larger copper–lead–zinc deposits in Dinantian rocks. Map drafted by Miss Margaret Lumley

thinking in terms of the 'new global tectonics' in his theory on the evolution of the Appalachian–Caledonian geosyncline.[13] Other work coupling drift theory with rift and trough formation has been published recently.[14,15]

In answer to Dr. Allum's questions on faulting, it is not known if the Riofinex Fault continues to the northeast. Examination of the small gravity anomalies[16] would appear to suggest that the long northeast–southwest fault deviates to the south rather than towards Garrykennedy. The status of the north–south fault in the southwest of Ireland is not clear. Different mechanisms for the formation of large faults with spacings of approximately 50–60 km have been advanced by Bullard,[17] Heiskanen and Vening Meinesz,[18] Kutina and co-workers[19] and Jung.[20] Jung[20] has remarked on secondary or intermediate faults midway between faults of 60-km spacing, although he envisaged a compressive mechanism. At this time I prefer to regard this fault as intermediate, although there is no evidence for the existence of a geofracture 30 km to the east this far south. It may continue to the north and I agree that it is worthy of investigation.

The writer is accustomed to the use of aerial photographs, but none was available. I am very interested in the suggestions of remote sensing put forward by Dr. Allum and Mr. R. W. Laing (pp. B45–7), and hope that they will be useful in the future. The kind of associated features to be expected are those suggested by Dr. J. W. Norman and Mr. M. V. OBrien (pp. B51–2), that is, later subsidence of Carboniferous rocks and a higher joint frequency.

The presence of galena associated with a north–south dyke of probable Tertiary age at Newtownards mentioned by Mr. Frank Yeates (pp. B47–8) is interesting. If, as Lamplugh[21] suggested, at least part of the ore was concentrated not earlier than the intrusion, the significance of the mineralization *vis-à-vis* the hypothesis is in some doubt. As Rhoden[22] has pointed out, however, it may be that the dyke took advantage of a preexisting lode. The presence of galena in a Tertiary sill, as well as in the underlying Triassic sandstone, which was demonstrated by boring near Conlig,[22] adds to the problem. Moorbath[23] accorded this lead an age of 420 m.y.±70 m.y., which would suggest at least some contamination from older rocks. I have not visited the area, so I feel unable to comment further, except to agree that if more than 1000 tons of lead was taken from the mine in 1852 and 1854, then it is likely to contain a good deal more in the unworked ground below the 40-fathom level, as well as making exploration to the north worth while.

Mr. Noel Gillatt asserted (p. B48) that the north–south faults in Ireland are Mesozoic in age. The most important of the north–south faults, the Kingscourt Fault, was active in Lower Carboniferous times. Jackson[24] has demonstrated that the vertical throw of this fault was 1 km in Dinantian times. Subsequent movement totalled more than another kilometre. This normal fault, then, affected sedimentation. No isostatic adjustment is necessary if fissures are vertical, and thus no sedimentation features would be expected near fissures 1 and 2.

Mr. Gillatt also says that the north–south dykes are Tertiary in age. A few of the Tertiary dykes are north–south; however, Charlesworth[25] noted 'innumerable (Devonian) felsite dykes running generally north–south over the northern half of the country'. Regarding the distribution of small lead–zinc deposits in eastern Ireland, the Conlig–Newtownards deposits and the lead showing at Swinley Point are north–south; old mines are also distributed along north–south lodes in the Castleblayney area.[26] My conclusions were not that the smaller sulphide deposits should necessarily lie on the hypothetical north–south geofractures. At the beginning of the paper (p. B117) it was pointed out that the 'low-grade high-tonnage ores [Gortdrum, Silvermines, Tynagh and Riofinex] contrast with most of the previously worked small sulphide deposits elsewhere in Ireland'. The conclusions to be drawn from the hypothesis were that exploration should be concentrated at the intersections of the postulated north–south fissures with cross faults. It may be significant that the recently announced Vale of Aherlow[27] copper–silver deposit lies on the Abbeytown–Gortdrum line 12 miles south of Gortdrum (Fig. 2).

In the original hypothesis I postulated that hyperbyssal intrusions had acted as 'hot spots', causing partial convective systems in pore waters in the upper crust. Only at Kilteely and Gortdrum is there any spatial relationship demonstrable between mineralization and igneous intrusives. It is true that the hypothesis does not explain the distribution of volcanic rocks in Ireland. Possibly this magma was formed below the crust and arose by penetrative convection, as envisaged by Elder,[28] finally reaching the surface in areas where the upper crust was weak. Bailey[3] has suggested that some alkaline magmatism could be due to the influx of volatiles into solid rocks in a 'dry' state in the lower crust, with temperatures above their 'wet' melting range. If this is so, then some 'hot spots' may have been caused by igneous intrusion, although the underlying cause would still be degassing of the mantle.

As there is no direct evidence bearing on the genesis of the Irish deposits, the source of metals was considered from several standpoints. A direct mantle origin was rejected because of the scarcity of lead–zinc and copper deposits in oceanic areas. However, chalcopyrite occurs in some quantity in a rhyolite agglomerate in southeast Iceland,[29] but this may have been leached from basalts, as suggested for occurrences in the southwest.[30] Also, the discovery of concentrations of zinc, copper and lead in brine pools along the median valley of the Red Sea[31] strengthens the case for a mantle source for these metals, as does the discovery of enrichment of metals in areas of high heat flow on the East Pacific Rise.[32] White,[33] however, believed that the metals in the Red Sea might have been derived from the sediments through reactions between circulating brines and clays and other minerals. The evidence against a mantle origin for lead and zinc deposits is not conclusive at this time, and it appears that copper may be derived from the mantle, albeit via a process of differentiation.

Some of the constituents of particular ore deposits may have been derived from intermediate magma, but Mr. Gillatt himself pointed out that the Lower Carboniferous igneous rocks lie along a northeast–southwest line and, hence, are seemingly unrelated to most of the ore deposits.

I quite agree that Carboniferous connate waters could have supplied the sulphur in the ore deposits, and isotope work may help to elucidate this problem. The Lower Carboniferous sediments may also have supplied some of the metal, as has been suggested by Boyle and Jambor[34] in their work on the Magnet Cove ore deposit at Walton, Nova Scotia.

The Lower Palaeozoic sediments appear to me to be the likely source of the bulk of the metal, but I accept that Carboniferous connate waters, with metal derived from Lower Carboniferous rocks, could also have contributed significantly to some of the mineral deposits. It was pointed out that the Abbeytown deposit was small (actually less than one-tenth of the size of Silvermines and Tynagh), as was to be expected from a consideration of the low permeability and reactivity of the underlying quartz–mica schist and gneiss.

I would like to thank Mr. C. J. Morrissey and his co-workers for their contribution (pp. B48–51) based on their own research. The remarks concerning igneous activity have been discussed above.

There seems to be some disagreement regarding the age of the first movements along the Tynagh Fault. It is clear, however, that the Lower Palaeozoic inliers, though they may have been islands in the Carboniferous Sea, did not have a high relief. I agree that the main vertical movements probably took place in the Mesozoic and/or Tertiary; the important question is whether this and other east–west faults were extant in Lower Carboniferous times. The evidence in favour of such an age for the Tynagh, Silvermines and Gortdrum Faults was given in the paper. Thompson[35] had previously postulated a common origin for the Gortdrum mineralization and the Viséan dykes, believing both the magma and the metal-bearing solutions to have been introduced along the fault zone.

The information that banded and colloform textures in sulphides are not indicative of a sedimentary or early diagenetic origin is important. Regarding the lead isotope results, these had been treated circumspectly by the writer.

The fact that mineralization occurred in advance of the north–south joints and faults does not detract from the hypothesis, since later surficial subsidence over a deeper weakness can be expected. The Abbeytown–Gortdrum and the Keel (Riofinex)–Ferbane lines do not affect sedimentation, and it was for this reason that they were classed as vertical fissures. It may be that these structures did not reach the surface, the excess pressure of the fluids perhaps finding an outlet along the east–west faults or into the porous Old Red Sandstone.

Morrissey and co-workers state that the Kingscourt Fault structure does not extend far southwards; gravity survey[36] results and the distribution of Namurian rocks[37] would suggest that it does. The Dinantian movements along the Kingscourt Fault have been remarked on above, and I suggested in the paper that the Castleblayney veins may mark the northerly extension of this fault. To the north of these veins Wright[38] postulated a north–south fold as the western margin of a trough and two synclines, the presence of which have been endorsed geophysically.[39] Although Wright regarded the folds in the Mesozoic rocks as being superimposed on steeper folds in the Carboniferous strata, there is no evidence of Upper Palaeozoic basins in northeast Ireland. Viewed in detail, Wright's western limiting anticline deviates to a north–northwest trend in the north. Fowler and Robbie[40] drew attention to a sharp correlation between the Drumkee Fault, with a throw of 3500 ft to the east, and the gravity anomalies. North of the Drumkee Fault a group of faults having the appearance of tension fractures due to folding trend north–northeast and north–northwest. To the north again, the Killymoon Fault trends north–south and has an easterly throw of 400 ft. On the downthrow side of this fault the Carboniferous Limestone dips 60° to the east. I suggest that the structures described above are part of a major north–south geofracture (3 in Fig. 2), 200 km long, with normal fault characteristics. The western boundary of Wright's North Channel Trough[38] is approximately 55 km to the east of geofracture 3, and may represent another geofracture of a similar type (4 in Fig. 2).

Morrissey and co-workers' preferred hypothesis for Irish mineralization involves the upward movement of highly saline solutions carrying metals leached from Palaeozoic rocks into structures reactivated by Armorican movements. No driving mechanism for the upward migration of these relatively heavy solutions is presented. The heating of the solutions to temperatures of 'well above 200°C' would require circulation to great depths[41] unless the heat flow were augmented by convecting igneous intrusions, volatiles from the mantle or a hybrid of both.

The map of all the copper, lead and zinc mineralization in Ireland is very useful, although some distinction between the magnitude of deposits is desirable since some contain 1 000 000 tons of metal but others only 100 tons. It is also important to distinguish between Caledonian and later deposits.

Elongation of the ore deposits along ENE–WSW faults is not at variance with the hypothesis. These cross faults would tap the upwelling fluids at shallow depth and the precipitation of metals would occur along such a fault. It is interesting to note that some of the smaller deposits unrelated to major east–west faults exhibit a north–south distribution, such as the Burren mines.[26]

I thank Dr. P. R. R. Gardiner (p. B51) for the information regarding the Foynes Trough. However, the present distribution of Millstone Grit in western Ireland is approximately north–south. His suggestion that the north–south and northeast–southwest structures of Carboniferous age were the synchronous components of a major fault set caused by tension in a northwest–southeast direction was considered. I agree that there may be a relationship between the two structural sets, but what is remarkable is that there is no basement control to explain the north–south geofractures. At depth the stress field associated with the Caledonian orogeny will have been largely dissipated by creep[42] and, tectonically, the governing factor is the Devonian–Carboniferous stress field. It is true that the present location of the Mid-Atlantic Ridge favours a northwest–southeast tensional system in the relevant area,[43] but it is likely that the Atlantic Ocean opened up in at least two stages.[11] The first movements possibly took place in the Devonian and Carboniferous. Webb[6] has suggested that the Labrador–Biscay Rift opened at this time. It may be that the Great Glen Fault transformed this rift to the Norway–Greenland Rhombochasm.[44]

The second spreading episode took place in Tertiary times[43] and, although in the direction suggested by Gardiner, is too recent to account for the Carboniferous structures. The comparison with the Red Sea is most interesting and an attempt has been made to draw a tectonic comparison between the two areas.[45]

The evidence for Carboniferous movement along the Tynagh and Silvermines Faults is important.

I agree with Dr. Norman regarding the possibilities of delineating the postulated geofractures from settlement in the Carboniferous cover. It may be that the small graben at the northern end of geofracture 2 is an obvious example of such settlement (Fig. 2). The discontinuous nature of the outcrop of sandstone at Castlerea may also be significant in this respect.

Mr. OBrien pointed out that, in detail, the western margin of Porcupine Bank is arcuate; however, it does trend north–south over a distance of 160 km. But this fact itself may not be significant since, according to the reconstruction of the North Atlantic continents along the 500-fathom (914-m) line by Bullard and co-workers,[46] there is an overlap of the south of Porcupine Bank with the Newfoundland shelf. This may be important as the rotation of Newfoundland has not been substantiated geophysically[7] and Black's[47] palaeomagnetic results are not statistically significant.[48] Stride and co-workers[49] have recently suggested a northward and westward translation of Porcupine Bank with respect to the continental margin west of Ireland, and pointed out that this would avoid the overlap mentioned above. Movement along the Great Glen and Cabot Faults was not considered by Bullard and co-workers,[46] so the reconstruction is necessarily very approximate in the region under discussion. Uncertainty regarding movements along these and associated faults leaves the exact form of the original rift in some doubt, but Stacey[50] has pointed out that many of the continental margin areas of Europe trend N 8° W.

It is true that the nearest part of the continental shelf is off the northwest coast of Ireland and trends southwest–northeast, but, as was pointed out above, this may be younger than the margin to the west.

Mr. OBrien says that many of the north–south joints may be due to Armorican pressures, but it is interesting to note Dawson-Grove's[55] suggestion that there was an east–west tensional regime in operation at the same time as the Armorican north–south compression in southern Ireland. I agree that north–south joints and dykes would seem only to have relevance if they were distinctly more frequent at 50- to 60-km intervals. The photogeophysics suggested by Dr. Norman and the remote-sensing approach of Mr. Laing and Dr. Allum may provide this test.

The Riofinex–Ferbane line was drawn adjacent to Old Red Sandstone inliers and extended northwards through a small graben, and southwards past the easterly end of the large Silvermine Mountains inlier. The ends of the inliers may be susceptible to local erosion levels, but it may be significant that the eastern end of the Mount Mary inlier adjacent to geofracture 1 correlates well with the eastern end of the Strokestown magnetic anomaly.[51]

As to strengthening the hypothesis, geofracture 3 is about 200 km long and may be demonstrated in part geologically and geophysically as outlined above. It is more difficult to delineate the postulated fissures, although the recent announcement of a copper–silver deposit in the Vale of Aherlow[27] lends credence to line 1, and the distribution of mineralization according to Morrissey and co-workers' map (Fig. 5, p. B49) may add support to line 2. What may be a similar type of structure in Scotland has been discovered by McLean and Qureshi.[56] They noted a north–south zone coincidental with Loch Lomond across which a marked change in the regional gravity field takes place. They also observed that several large fractures are deflected across the southerly projection of this zone.

Lead–zinc–barytes deposits in the Lower Carboniferous rocks of the Maritime Province of Canada are apparently similar to those in Ireland, but the age of mineralization is unknown. According to McCartney and McLeod,[52] numerous mineral occurrences and deposits occur along a major east–west fault zone to the west of the West River St. Mary—for example, at Walton, Brookfield and Smithfield. This fault direction is parallel to the continental margin in this area. Small deposits of barytes also occur along an east–west fault north of Cobequid Bay, Nova Scotia.[52] These faults may have been caused by the splitting apart of Africa from the Maritime Provinces. However, the faults are parallel to the Appalachian trend and other mechanisms may explain them. Howie and Cumming[53] believed that fragmentation and subsequent tilting of basement blocks during the Carboniferous would have led to isostatic adjustments, subsequent erosion, and then sedimentation of thick terrestrial sediments in localized narrow troughs which trend approximately east–west and north–northeast.

Regarding the Abbeytown deposit, it was not my intention to suggest that all Irish ore deposits were strata-bound but merely to make the point that they were more similar to this deposit than they were to the vein sulphides.

The statement remarking the presence of bornite and chalcopyrite in the Old Red Sandstone in the south of the country was from Jukes.[54] My own work on trace-element geochemistry points to an enrichment in a sandstone 3 m thick of up to 650 ppm of copper 100 m below the Old Red Sandstone–Carboniferous boundary at Hook Head. I thank Mr. OBrien for his correction regarding the silver content at Silvermines.

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Abstracts

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The geology and the ore mineralization in the Keban area, east Turkey

M. Tuncay Kines

Ph.D. thesis, University of Durham, 1969

The Keban mine is one of the most important lead and zinc producers in Turkey. It is located 54 km northwest of Elaziğ county, eastern Turkey. The Keban metamorphic massif consists of calc-schists, dolomite marble, phyllite and marble. It forms part of the eastern Taurid belt—a prolongation of the Alpine orogenic belt. The principal structural feature of the area is the northern extension of the Malatya–Keban anticline—a major recumbent fold with a NE–SW axis. Later movements, acting in different directions, gave rise to N–S, E–W, NW–SE and NE–SW directed folding and faulting over the previous anticline. Small bodies of quartz–syenite porphyry, of Palaeocene age, intrude the metasediments.

Detailed study by chemistry, petrography and X-ray techniques on sanidine accounts for a composition range between $Or_{65}Ab_{35}$ and $Or_{99}Ab_1$. The ratio of Or to Ab tends to increase outwards from the central parts of the igneous body.

Skarn zones have developed in association with the intrusion of quartz–syenite porphyry. These are located mainly within the metasediments. The magnetite deposit of Zereyandere, the scheelite deposit of Kebandere and the main sulphide deposit were formed as part of the process of skarn formation. Minor amounts of some manganese minerals, and the minerals vanadinite and descloizite, derived from the main sulphide deposit, are also found in the district.

The main sulphide deposit of economic importance chiefly includes sphalerite, galena, iron and copper sulphides and several sulphosalts in subordinate amounts. Of the by-products, silver comes from galena, polybasite and tennantite. Arsenopyrite, in addition to chalcopyrite, contains trace concentrations of gold.

All the evidence suggests that the quartz–syenite porphyry is the source of mineralization. The location of ore minerals is controlled by certain rock types and by major and minor structural elements. Variation of vapour fugacity and temperature during mineralization are indicated by more than one stage of formation for certain ore minerals. The presence of different gangue minerals marks the fluctuating nature of the ore-forming fluids, whose last stage is believed to be alkaline rather than acidic.

The main sulphide deposit is accepted as a semi-metasomatic contact deposit, and the magnetite and scheelite deposits are classified as being contact metamorphic.

By the use of various methods, a temperature range of formation between 620 and 78°C is estimated for the ore minerals of the main sulphide deposit. For the ore minerals of the scheelite and magnetite deposits, the range is from 743°C to 225°C.

Geological history of the Precambrian rocks in parts of the Porcupine mining area, Canada

J. L. Kirwan

Ph.D. thesis, University of London, 1968

Archaean rocks of the area make up three depositional series which are separated in time one from another by periods of folding. The oldest rocks, exposed in the southern areas, consist of marine-laid basic lavas overlain by felsic volcanics and clastic sediments, all sheared and folded in a northwesterly direction. During the folding regional metamorphism to the greenschist and amphibolite facies and intrusion of gabbro and ultrabasic rock took place.

The medium-aged rocks were deposited in a broad geosyncline, which deepened to the north. In the central parts of the area shelf facies deposits consist of basic lavas overlain by felsic agglomerate and coarse clastic sediments, but northward these rocks give way to uniformly banded fine clastic sediments deposited in a deeper sea environment. During the later stages of volcanism and sedimentation the rocks were folded synchronously along north–south and approximately east–west lines and metamorphism to greenschist and amphibolite facies took place. Domal structures controlled the locations of volcanic centres, igneous intrusion and orebodies.

The youngest group of rocks, which occurs in the northwestern area, was folded along dominantly east–west lines. Metamorphism of the original sedimentary rocks to gneisses of the high amphibolite facies may have taken place at this time.

Faulting and the related intrusion of diabase dykes along north–south, northeasterly and northwesterly lines took place as uplift occurred in the northern areas during Proterozoic time. Widespread, severe retrograde metamorphism accompanied the faulting.

Glacial, glacial–lacustrine and fluvioglacial deposits of Pleistocene age now cover most of the bedrock to depths which range up to 400 ft.

A study of recent carbonate sediments around the principal islands of the Seychelles and on the Seychelles Bank

M. S. Lewis

Ph.D. thesis, University of London, 1966

The Seychelles Bank, a submarine platform of 31 000 km², is composed of continental material and veneered by skeletal carbonate sediments. Granitic islands rise from the centre of the Bank, which has a shallow rim. Submarine terraces reflect Pleistocene sea-level changes.

The carbonate sediments range from coralline algal/benthonic foraminiferal sands to fine sediments composed of pelagic and small benthonic organisms. Two facies are described. Algal cobbles occur on the shallow rim. Quartz is found in sediments around the granitic islands and terrigenous calcite crystals also occur.

Grain-size measures reflect terrigenous and skeletal composition. Sediments near the rim contain little fine material and were formed under oxidizing, turbulent conditions; those on the central parts of the Bank are rich in fines and were deposited in quieter, reducing conditions in which syngenetic pyrites and phosphate were formed.

Fringing coral reefs occur around the granitic islands. Around Mahé two types are recognized: well defined, windward reefs and patchy, sheltered reefs. Buttresses and grooves are developed on the former; channels dissect the latter. Two submarine terraces occur at −10 m and −22 m.

The windward reef flats exhibit a well defined ecological zonation, which is ill defined on the sheltered reefs. The zones provide distinctive sedimentary environments. The associated sediments are clastic skeletal carbonates with quartz limited to special environments. They are composed largely of coralline algal and coral grains, with variable amounts of other fragments.

Grain-size measures are controlled by environment, currents and composition. They are not always related to the zonation. Most sediments are sand-grade, but cobbles are common. The sediments are largely composed of aragonite so that corals are more important contributors than coralline algae.

Beach rocks are of widespread occurrence. Remnants of raised limestones are found up to 12 m above mean low water.

TECTONIC COMPARISON OF NORTH ATLANTIC AND MIDDLE EAST RIFTING

By

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and

A. BURGESS

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Tectonic Comparison of North Atlantic and Middle East Rifting

THE recent paper by Gass and Gibson[1] draws attention to tectonism related to rifting due to differential velocities of adjacent continental segments.

We wish to compare the fracture patterns related to the formation of the Red Sea Rift with those related to the opening of the Labrador–Biscay Rift described by Webb[2]. In doing so, striking similarities become apparent which may have general significance in the study of rift zones.

Webb[2], using Wilson's concept of transform faults[3,4], interprets the sinistral movement along the Great Glen Fault, and the dextral movement along its counterpart, the Cabot Fault, as due to the "Labrador–Biscay" rifting between Western Europe and Newfoundland. Evidence from the faulted areas suggests a Devonian–Carboniferous age for the rifting. This is supported by the geophysical studies of Sheridan and Drake[5]. Unlike the margins of the Red Sea Rift it appears that those of the Labrador–Biscay Rift moved apart in opposite directions. The regional fracture pattern of the western part of the "Arabian Segment", however, appears similar to that of the British Isles as interpreted by Webb[2] and Russell[6] (Figs. 1 and 2).

Russell[6] has suggested that north–south geofractures and faults which were formed as the result of east–west tension related to continental rifting in Devonian–Carboniferous times occur in Ireland. These geofractures seem to bear the same relationship to the Great Glen Fault as do those of the "Arabian Segment" to the Jordan Shear. Also included in Fig. 2 is the large north–south geofracture in England, taken from Dunning and Stubblefield[7]. The evidence for the geofractures in Ireland is the distribution of large base metal deposits[6], a fault[8] and monoclines[9]. The Irish mineralization has been compared with that of the western margin of the Red Sea, and that in the Red Sea itself[6].

We believe that the Irish geofractures may be considered as jointing, on a very large scale, in the Earth's brittle crust, due to east–west tension. The nature of the geofractures will be determined by the interaction of positive pore pressures and the strength parameters of the rocks. Tensile failure will result when pore pressures are high, and normal fault compressive failure when they are low or absent. It is probable that in rift areas high positive pore pressures may be developed due to mantle degassing. The north–south geofractures in Ireland are separated by distances of between 50 to 60 km. Kutina *et al.*[10] had previously noted geofracture spacings of this range in Czechoslovakia. By analogy with the joint model proposed by Price[11], regular spacing of the geofractures would be expected.

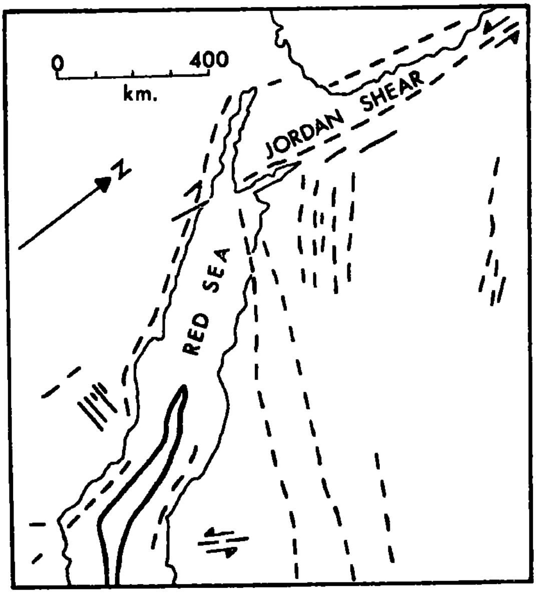

Fig. 1. Arabian Segment and Red Sea re-drawn from Gass and Gibson[1]. Thick line, continental margin: thinner lines, faults.

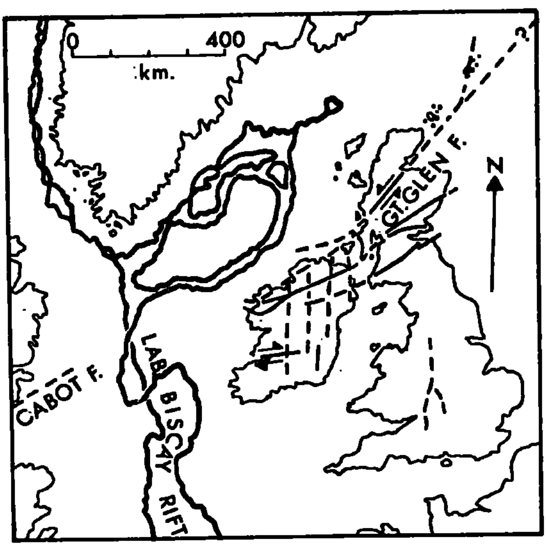

Fig. 2. North Atlantic region from Bullard *et al.*[15], Webb[8], Russell[6], Dunning and Stubblefield[7]. Thick line, continental margin; thinner lines, faults and fissures.

The wrench faults along the eastern margin of the Red Sea are possibly comparable with the east–west dextral shears in Ireland noted by Charlesworth[12] and Rhoden[13]. This shearing was formerly ascribed to the Hercynian orogeny but may now be more easily understood in terms of differential movement of the continental margin away from the Labrador–Biscay Rift.

We wish to ask Gass and Gibson if the major north-westerly trending faults in the western part of the "Arabian Segment" are approximately equally spaced, and if so, what are the distances between them? Also, are the fault planes characteristic of normal faulting or vertical fissuring, or of both these types? A further question concerns the basalt feeders in the area under discussion. Westoll[14] has pointed out that the Carboniferous basalts in the British Isles may be related to continental drift. The basalt lavas were extruded from volcanic centres which often occurred along the north-east–south-west trending Caledonian lines of weakness. The later dykes, however, have an east–west trend and may have arisen from shears at the base of the lithosphere caused by differential movement away from the rift. Are there recent dykes with a north-east trend in the Arabian Segment?

If the two areas shown in Figs. 1 and 2 are comparable, then the intersections of north–north-east wrench faults with north-westerly trending tension fissures, or faults, in the Arabian Segment may be favourable sites for mineralization. The size of any mineral deposit would, however, depend on the availability of metals and sulphur in the crust, as well as the presence of suitable host rocks[6].

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North–south geofractures in Scotland and Ireland

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Synopsis

The suggestion is advanced that north–south trending faults and Carboniferous synclinal troughs, as well as a crustal inhomogeneity in central Scotland, were formed in response to a stress field in which the direction of relative tension was oriented east and west relative to the present pole. These structures are considered to be higher homologues of three major extension failures (geofractures) at the base of the Upper Crust which are separated by distances of 45 and 55 km. In Ireland (like Scotland, situated close to the continental margin) north–south geofractures have previously been postulated to explain the distribution of major ore deposits (Russell 1968, 1969).

Sparse stratigraphical evidence points to a late Tournaisian or Viséan age for the initiation of the postulated geofractures. They are considered to constitute the earliest evidence for the stress field that eventually caused lithosphere separation at Rockall Trough. This separation is inferred to have taken place at the end of Carboniferous times.

Introduction

The major base metal deposits in Ireland are generally associated with faults trending approximately N 80° E, some of which were in motion in Dinantian times. Although these local structural controls of ore deposition are clear, the structures and agents determining the regional distribution are obscure. The pattern of regional mineralisation may be explained by postulating a set of major geofractures, trending north–south (Russell 1968). These major extension failures in the base of the upper crust are now considered to be linear zones of tensile failure, manifest at higher levels, not as simple discrete faults, but as zones of structures up to 10 km wide aligned north and south and anomalous in their regional context. The anomalous structures may be normal faults, minor rifts, synclinal troughs or monoclines of meridional trend. They are evenly spaced at intervals of 50 to 65 km and this spacing may be explained by existing theories of rock mechanics (Burgess 1969; Russell and Burgess 1969).

The parallelism of the postulated geofractures to the neighbouring Atlantic margin and gravity anomalies to the west of Ireland (Russell 1968, p.120 and fig. 2) seemed significant, and was the basis of a further suggestion that the geofractures formed in response to a stress field in which the direction of relative tension was oriented east and west relative to the present pole. This stress field was considered to have been the cause of the first stage of rifting in the North Atlantic region.

Gray and Stacey (1970) have since published their geophysical results and show free-air anomalies with north–south trends to mask progressively the effects of the Caledonian fold belts towards the continental margin.

Although the hypothesis offered a model of developing crustal structure consistent with recent theories of the initiation of sea-floor spreading, the evidence available was too limited to test adequately its validity. Whereas the Kingscourt geofracture in eastern Ireland is structurally well defined (Russell 1969, p. 130 and fig. 2), the definition by outcrop of two others (the Abbeytown–Gortdrum and the Keel–Ferbane geofractures) is poor, and the hypothesis rests on relatively few large mineral deposits. The additional evidence to strengthen the hypothesis and define the pattern could come from (1) the location of further mineral deposits in Ireland, thus providing not only new points in the pattern, but more significantly experimental support, or otherwise, for the postulated model; and (2) recognition of similar structures, and similar associations, in regions comparably located close to the Atlantic (Rockall Trough) margin.

Regarding the first point, two mineral deposits have been discovered in Ireland since the model was proposed. Syngenore have found a zinc-lead deposit at Ballinalack, Co. Westmeath, 18 km due east of the Riofinex deposit at Keel (Fig. 3). The siting of this deposit is obviously not explicable in terms of the hypothesis. A major base metal deposit has been discovered recently by Tara Exploration. Lying 1·5 km north-west of Navan in Co. Meath, it falls 6 km east of the previously postulated Kingscourt geofracture (Russell 1969, p. 130 and fig. 2), identifiable in this region by a meridional trend to the Bouguer anomaly contours (see Murphy 1962). This discovery, shown in relation to the Kingscourt outlier in Figure 2, supports the hypothesis.

Scotland fulfills the second requirement, and the purpose of this paper is to draw attention to the evidence of three similar geofractures in this country. Some of the features associated with the Scottish geofractures are found to occur also along the previously postulated Abbeytown–Gortdrum geofracture in Ireland (Russell 1968, p. 123 and fig. 1).

Post-Caledonian mineralisation in Scotland

Several workers have attempted to define belts or lines containing or intersecting most of the mineral deposits in central and south Scotland. MacGregor (1944, pp. 4–5) pointed out that many of the veins of barytes and other minerals occured in a belt about 24 km wide aligned approximately north-west–south-east and lying within the Mull dyke swarm. This belt included the Leadhills deposit.

More recently Kutina (1968, fig. 7) has constructed an empirical prospecting net for western Scotland, in which he derived a set of hypothetical north-north-west faults as a complementary set to the Caledonoid (north-east–south-west) trending wrench faults. Many of the ore localities occur at or around his intersection.

As in Ireland, there are many small sulphide deposits in Scotland. In Figure 1 only those three mines in post-Caledonian sulphide deposits on the mainland of

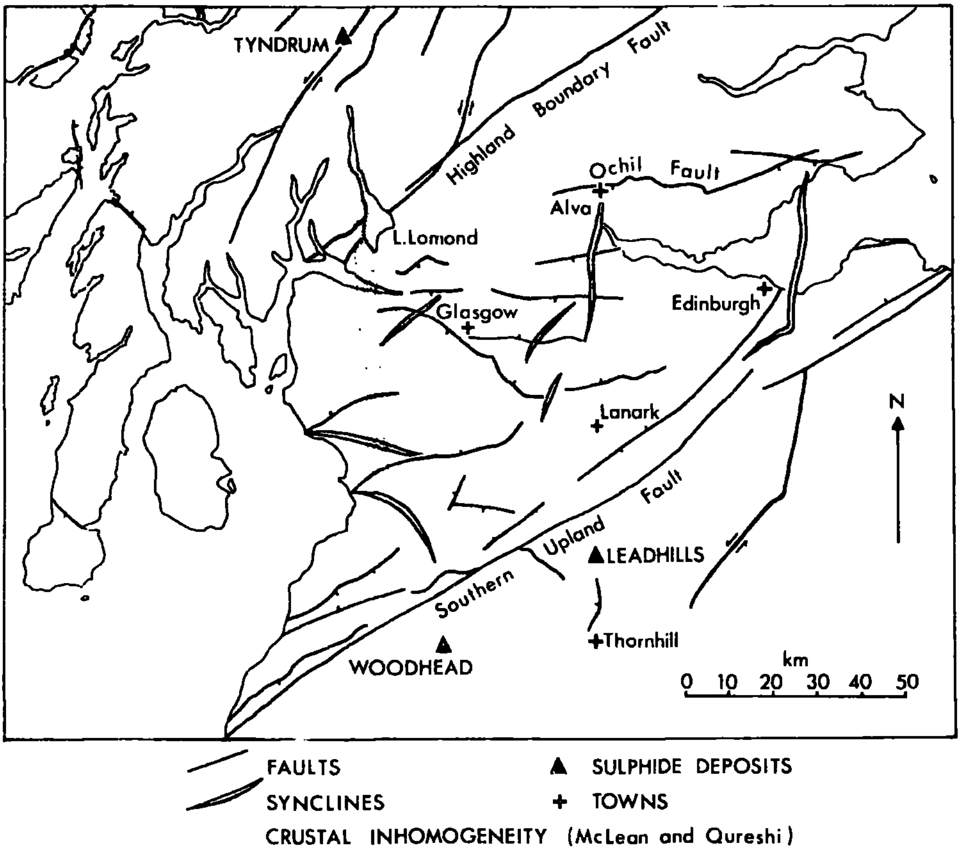

FIG. 1. Map of south-central Scotland showing faults, Carboniferous synclinal troughs and post-Caledonian sulphide deposits known to have produced more than 5000 tonnes of high-grade ore. Based on Dunning (1966), McLean and Qureshi (1966), Wilson (1921) and Park (1961).

Scotland, known to have produced over 5000 tonnes of high grade ore, are marked (Wilson 1921). The sparse evidence considered by itself is totally inadequate to define a pattern of regional distribution of these deposits. Local concentrations are controlled by faults and joints which trend north–south at Leadhills (MacGregor 1944, p. 5) and north-east–south-west at Tyndrum. But in each case the single set of fractures does not, by itself, explain a point concentration of ore and the presence of a transverse structure must be postulated.

Major north–south structures in Scotland

The Loch Lomond crustal inhomogeneity

McLean and Qureshi (1966, pp. 272–3 and fig. 1) discovered a north–south zone approximately coincident with Loch Lomond in west-central Scotland, across which there is a marked change in the regional gravity field (Fig. 1). They observed that the Dusk Water and Inchgotrick Faults and two Permo-Carboniferous dykes were deflected across the southerly projection of this zone. It is interesting to note here Kutina's suggestion (1968, p. 106) that a rupture may have been responsible for the elongated form of Loch Lomond and that his hypothetical north-north-west line drawn through the Loch intersects the Tyndrum Fault at the Tyndrum mining district. The northward extrapolation of the ' McLean–Qureshi crustal inhomogeneity ' (Fig. 1), however, intersects that fault in the region of the richest mineralisation (see Wilson 1921, pp. 93–102), so that a more directly north–south control is assumed here.

The demonstrated length of this meridional peculiarity in the crust, considered here to be another example of a geofracture, is about 75 km and it may continue northwards and be responsible for the concentration of ore at Tyndrum.

The postulated Alva–Thornhill geofracture

The Leadhills–Wanlockhead vein system was the largest producer of lead and zinc in Scotland (Wilson 1921; Mackay 1959). About half a million tonnes of ore have been removed and the lodes are still not exhausted. In mineral content and dimension, though not in form, this deposit is similar to some of the post-Caledonian base metal bodies recently discovered in Ireland. It is different from the North Pennine ore field in that it contains no fluorite and is not known to have a wide lateral extent.

MacGregor (1944, p. 5) has pointed out that ' the trends of the Leadhills and Wanlockhead veins are parallel to and on the line of faults, with trends a few degrees W. or E. of N., that cut the Permian sandstones and lavas of the Thornhill outlier of Carboniferous rocks a few miles to the south ' (Fig. 2). Mykura (1965, p. 15) has since shown that the ' Permian ' sandstones of Thornhill are probably of Upper Carboniferous age. George (1965, p. 25) considers this outlier to have been a comparatively small syncline in the Southern Upland Massif in Upper Carboniferous times.

The northerly extrapolation of the Thornhill–Leadhills structure approximately coincides with Hall's Lanark Line (Hall 1971) which in turn passes into a north–south syncline that contains the Stirling, Clackmannan and part of the Central Coalfields (Fig. 1, and see Dunning 1966). From isopachyte measurements, Goodlet (1957, 1959) has demonstrated that this was one of several synclines in the

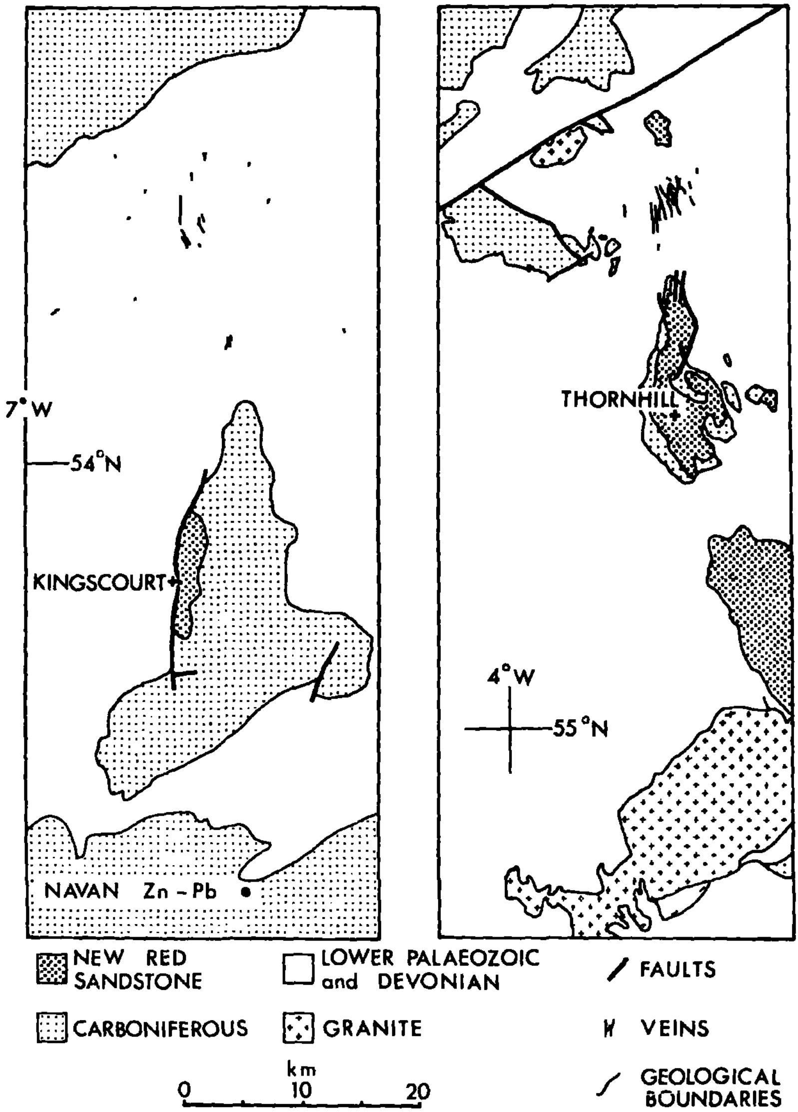

FIG. 2. Comparison of the Kingscourt outlier (Ireland) with the Thornhill outlier (Scotland). The Castleblayney veins occur to the north of the Kingscourt outlier and the Leadhills–Wanlockhead vein system to the north of the Thornhill outlier. Both structures are considered to be components of north-south geofractures. Tara Exploration's new zinc-lead discovery near Navan is also shown. (Geology plotted from the published sheets of the Geological Survey of Ireland One-Inch Map and the Geological Survey One Inch Map of Scotland.)

Midland Valley of Scotland that were the sites of subsiding troughs during the Carboniferous, at least from upper Viséan (P_2) times.

The axis of this synclinal trough abuts the east–west Ochil Fault at its point of maximum throw (approximately 3 km down to the south, in Francis *et al.* 1970, pp. 246–7). Twenty-two kilometres to the west, this fault dies out completely (ibid., p. 246). Francis *et al.* (ibid., p. 247) infer the Ochil Fault to have separated a relatively positive area of slow subsidence to the north from a much greater, more continuous subsidence to the south in Carboniferous times. They also point out that a fault of the same trend may have existed before Upper Old Red Sandstone deposition (ibid., p. 247).

Several veins containing chalcopyrite and barytes, with lesser amounts of galena, erythrite and argentite, occur to the north of the Fault, notably near to and just to the west and north-west of Alva (Wilson 1921; Geological Survey One-Inch Map of Scotland Sheet 39: (Stirling)).

It is suggested here that the Thornhill syncline is a structurally higher homologue of a geofracture which continues northwards and is occupied by vein minerals at Leadhills. The much larger syncline to the north may be the result of some thinning of a more ductile crust.

The overall length of the postulated Alva–Thornhill geofracture is at least one hundred kilometres.

The postulated Buckhaven–Innerleithen geofracture

Two structures, a fault and a syncline, with Caledonoid trends deviate to a northerly direction along a line 45 km east of the postulated Alva–Thornhill geofracture (Dunning 1966) (5 km east of Edinburgh on Fig. 1). Goodlet (1957, 1959) has demonstrated that this syncline too, containing the East Fife and Midlothian coal basins, was in existence in upper Viséan times, and continued subsiding throughout much of the Carboniferous. No major mineralisation is known to exist along this structure but its similarity to the Alva–Thornhill structure leads me to consider this to be another example of a geofracture.

Comparison of the Scottish north–south structures with the postulated geofractures in Ireland

The Ochil Fault, which forms the northern boundary of a contemporaneous north–south syncline, resembles structures in Ireland which also control mineralisation. One area, that of the Tynagh Mine, shows the Ochil structural pattern on a smaller scale. According to Schultz (1966, p. 321) the North Tynagh Fault has a maximum downthrow of about 600 m to the north. The throw lessens to the east and west and may give way partly to increases in the strike slip component. The mineralisation is especially concentrated in the region of maximum throw. Moreover, about half a kilometre to the north-north-west, an east–west section (ibid., fig.3) reveals a thickening of a mid-Dinantian sedimentary iron deposit in the deepest part of a basin. Thus there appears to have been subsidence on the line of the postulated Abbeytown–Gortdrum geofracture in mid-Dinantian times in this region.

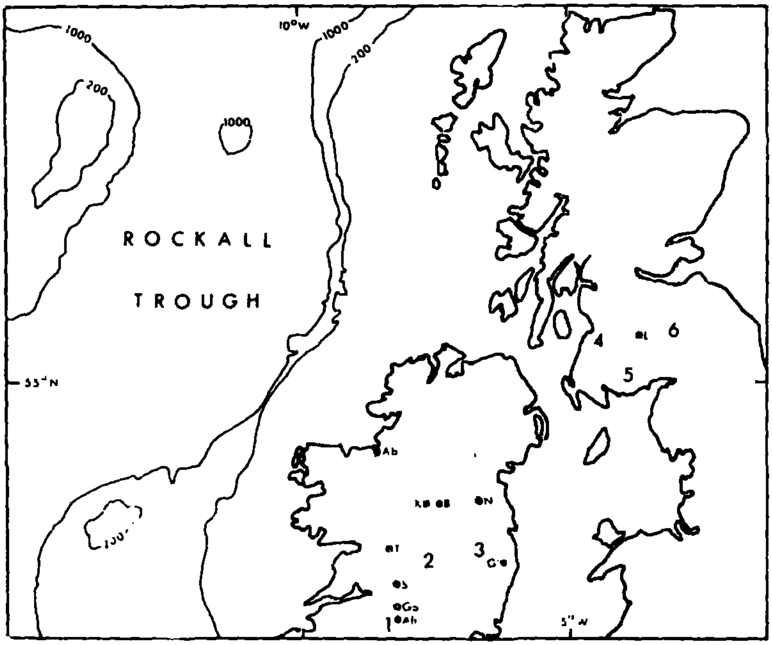

FIG. 3. Mercator projection showing the relationship between Rockall Trough and the postulated north-south geofractures in Scotland and Ireland. Bathymetry in metres (Stride *et al.* 1970; Roberts 1970).
Geofractures are numbered as follows:
1, Abbeytown-Gortdrum; 2, Keel-Ferbane; 3, Kingscourt; 4, Loch Lomond; 5, Alva-Thornhill; 6, Buckhaven-Innerleithen. Geofractures 1-3 are modified from Russell (1968, 1969). Post-Caledonian sulphide deposits in Scotland and Ireland with more than 40,000 tonnes of base metal are lettered as follows: Ab, Abbeytown; T, Tynagh; S, Silvermines; Go, Gortdrum; Ah, Aherlow; K, Keel; B, Ballinalack; N, Navan; Gl, Glendalough; L, Leadhills.

The Slievenmuck Fault, trending east-north-east, also achieves its maximum downthrow (1700 m north according to Mahbub-i-Khuda in Shelford 1963, p. 262) crossing the proposed Abbeytown–Gortdrum geofracture (Russell 1969, fig. 2) 2 km north-north-west of the copper silver deposit at Aherlow. In this case, however, nothing is known of the relative thickness of the Carboniferous strata on the downthrow side.

The deflection of structures across the projection of a north–south zone in Scotland (McLean and Qureshi 1966, pp. 272–3) also has a counterpart in Ireland. To the west of the postulated Abbeytown–Gortdrum geofracture most faults trend between east–west and 10° north of east (Weir 1962, pl. 8: Geological Survey 'Twelve Mile' Map of Ireland, Dublin 1962), but to the east the predominant direction is between east-north-east and north-east (see also Russell 1968, fig. 1).

The Thornhill Basin–Leadhills structure affords a view of part of a north–south geofracture. It is remarkably similar in outcrop pattern to the Kingscourt outlier and the accompanying Castleblayney veins in eastern Ireland (Fig. 2), which form part of a larger north–south geofracture (Russell 1969, p. 130 and fig. 2).

Discussion and conclusions

Two of the three Scottish major north–south structures described above include subsiding troughs as component parts. The formation of the troughs is best explained by a stress field in which the direction of relative tension was oriented east–west. The Loch Lomond crustal inhomogeneity does not, in itself, indicate east–west extension but its parallelism with the other structures and with part of the continental margin to the west of Scotland argues for its inclusion into the set of geofractures. The north–south subsiding troughs are located within Caledonoid trending blocks and do not appear to extend to their margins. The Stirling–Clackmannan and the East Fife–Midlothian troughs lie within the Midland Valley of Scotland and the Thornhill and Kingscourt outliers within the Lower Palaeozoic Southern Upland block and its continuation in Ireland. This suggests that within blocks, east–west tension is released by crustal thinning, whereas on their margins it may be dissipated partially by shearing movements along a Caledonoid ' free-surface ', such as the Southern Upland Fault.

The Scottish meridional structures described are separated by distances of 45 and 55 km. This is similar to the observed 50 to 65 km spacing of the postulated geofractures in Ireland. According to the present evidence the geofractures in Ireland date from late Tournaisian or early Viséan times (Russell 1968, p. 122; 1969, pp. 129–30). The age of similar structures in Scotland is less easy to determine. They certainly affect upper Viséan sedimentation (Goodlet 1957, 1959) and the Lanark Line (Hall 1971) was in existence in mid-Dinantian times, but information beyond this is lacking.

Although a relationship can be demonstrated between observable north–south structures and two of the larger post-Caledonian sulphide deposits in Scotland, there is no such control of the Woodhead deposit (Fig. 1). Also there are many lodes and veins in Scotland that apparently occur independently of the inferred set of north–south geofractures (see Wilson 1921). So no claim is made that post-Caledonian sulphide mineralisation is always dependent on these structures.

A problem not resolvable in terms of the hypothesis is the east–west trend of the quartz dolerite dykes of Stephanian age (Walker 1935; Tomkeieff 1937; Francis 1967). These dykes imply a stress field in which the minor principal stress direction was oriented north and south (Anderson's Borcovician—Anderson 1951, pp. 31–43). A consequence of crustal stretching in an east–west direction would have been to reduce north–south compression, perhaps causing east–west faulting, but we would have expected the dykes to rise along north–south breaks and this has not happened. Within the north–south syncline in the Central Coalfield, however, there is some concentration of dykes and sills, suggesting that this structure could have been a focal point for the intrusives. Powell (1970, p. 367 and fig. 2) explains a magnetic anomaly, 25 km north of Lanark, as a body 16 km in diameter with its top 5 km below the surface, and notes that a gravity ' high ' on its western flank implies a rock denser than granite. It is possible that this magnetic source is a body of similar composition to the quartz dolerite intrusives but at a deeper level.

The magma forming the dykes and associated sills must have been derived by shallow partial melting of the mantle (e.g. Kushiro 1968; and see Harris 1970, table 1). Tholeiitic magmatism is to be expected during a time of continental break up (e.g. Gass 1970) and this magmatism along with the preceding and contemporaneous alkali igneous activity had ceased abruptly by the end of Carboniferous times (Francis 1967). Bott and Watts (1970, p. 101) suggest that ' the Rockall Trough may have formed or been forming as a Red Sea type trough in Permo-Triassic time '. Lithosphere separation in this region at the end of the Carboniferous period would explain the cessation of magmatism in northern Britain in that it would have provided a new site for igneous activity. Such separation may have been beneath particular north–south geofractures and weakness planes of approximately Caledonoid trend. The tensile stress concentration at the bottom of a geofracture would have caused increasing strain in the lithosphere and on final separation ocean floor spreading would have commenced.

Acknowledgements

I should particularly like to thank Dr Adam McLean and Dr Tony Burgess for their continued interest and help. I was also fortunate to have stimulating discussions with Dr J. Jackson, Dr W. A. Read, Professor T. Murphy, Mr M. H. Smith and Dr P. Gardiner. Mr M. V. OBrien and Dr R. W. Schultz read an earlier draft of the manuscript and I am grateful for their suggestions. None of these men should be held accountable for the views expressed here. Finally I should like to thank Professor A. Kerr Pringle for his encouragement and support.

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Volume 78 1969

Discussions and contributions

Structural controls of base metal mineralization in Ireland in relation to continental drift

M. J. Russell

fracture in the boulder clay, then the cause of the surface lineaments needed further investigation. It was not easy to understand the link between a fault in bedrock and its reflection as a lineament on top of a cover of undisturbed boulder clay 100 ft thick.

The Chairman said that he had not been able to find in the paper any statement as to the scale or scales of the photographs that had been used in the investigation. He knew that a great deal of the aerial photography of the United Kingdom was on the 1 : 10 000 scale, and supposed that that had probably been used in the present work. Much photography overseas, however, was at 1 : 40 000 scale or even 1 : 80 000. Use of photography of those scales could mean a considerable difference in the style of the photogeological approach, and he asked if it would be possible for the author to include a short statement as to the scale of the photography used.

W. Willox* said that probably the most important thing which came out of Dr. Norman's paper was the fact that without photogeology one did not map a great many features. Those familiar with photogeological maps would remember that they always saw a great many fractures and structural features on them; on the other hand, geological maps prepared mainly in the field, even the very excellent ones of the British Geological Survey over the past century, were noticeably deficient in fractures, at least in the density one came to expect on photogeological maps; and that was an indispensable additional tool.

Dr. Norman's paper probably posed more questions than it answered, and he would like to ask two at the present time. First of all, in Table 4 (p. B64) there was an extremely remarkable similarity in the results. Soil boundaries, soil forms, lithological boundaries and bedrock topography were almost exactly the same length, and he wondered to what extent Dr. Norman thought that those might be due to subjective factors or, if not to subjective factors, to physiological optical factors. His second question related to the sort of thing the practising photogeologist wanted, i.e. data of practical help. Dr. Norman mentioned under Table 5 (p. B64): 'Joints . . . were also short; only 2 per cent of those causing lineations exceeded 1100 ft'. He asked if it was possibe to use the length of the lineations, or lineaments as he preferred to call them, to distinguish between different features, such as faults and joints. Could one say that if the feature in a particular area was generally less than 1100 ft it was most unlikely to be a fault, but that there was a 90 per cent probability that it was a joint? That perhaps was something which needed further investigation.

Finally, he made a suggestion for future research. Although he was sure Dr. Norman already had enough problems he would add one more. In tropical savannah terrains where the grass was burnt off, a number of patterns commonly developed. Some of those patterns were undoubtedly due to the changing effects of wind and burning at different times, but in some cases there was undoubtedly a reflection of the bedrock geology, even though the ground was covered by a considerable thickness of residual soil and laterite. Unfortunately, between those two cases there was an enormous number of absolutely uncertain cases where one could not be sure to what the patterns were due. If attention could be paid to that problem in the future, especially to work in Africa, it could be of great value to people engaged in mineral exploration in the underdeveloped countries.

Contributed remarks

Dr. Ian Nichol On reading Dr. Norman's paper, and in listening to the discussion, it appears that the problems of interpretation of the data may be broadly similar to those facing us in the interpretation of geochemical data and, for that matter, in the wider geological field as a whole. In general, the problem is one of relating observations or variables to the factors affecting their formation.

If I may digress briefly, I will describe the geochemical problem. In geochemistry it is frequently necessary to relate the minor-element distribution to the factors affecting its formation, normally bedrock type, surface environment and mineralization. Insofar as the composition of stream sediments is a composite of the material upstream from the sampling point, it is variously related to a number of controlling factors within the catchment area. It is frequently not easy, especially where the geological control is poor, to decide with any degree of confidence the extent to which the minor-element distribution is attributable to these various influences.

As an aid in the solution of this problem we have employed the multivariate technique of factor analysis. Essentially, factor analysis establishes the interrelationships of the variables, in this case minor elements and the end members, various combinations of which would serve to account for the majority of the overall data variability. It may be shown that essentially all the information on some 13 minor elements can be described in terms of some six or seven factors, giving rise to a considerable simplification of the data. In addition, where a particular variable or minor element is controlled by two factors operating in an area, factor analysis redistributes the data relating to this element between the two controlling factors. Similarly, this approach may lead to the recognition of new relationships in the data not recognized previously because of the apparent complexity of the variables.

Considering the interpretation of serial photograph data, the basic problem appears somewhat similar, i.e. the recognition in the present example of characteristic features by which the cause of lineaments may be identified. In this context the collection of ancillary information relating to the lineaments is an essential preliminary to identifying the association of different characteristics with lineaments of differing origin. Factor analysis would draw attention to any relationships existing between lineaments and other variables, some of which might not have been previously recognized. In this way both variables significantly associated with lineaments of varying type and those variables of no importance in the diagnosis of the provenance of a lineament would be recognized.

If such an approach is applicable to the interpretation of aerial photograph data, it would seem desirable to consider the incorporation of a number of variables which, on first consideration, might be thought to be of little value. This approach would give rise to the possibility of recognizing any hidden relations between linear features and variables. Such an approach seems preferable initially to that of testing subjective hypotheses, which, no matter how soundly based, could not lead to the identification of any significant new relations. If the hypotheses were correct, then this, of course, would be confirmed by the factor analysis solution.

I now leave it to those familiar with the problems of interpretation of aerial photograph information to judge whether factor analysis can be of any assistance to the solution of their problem.

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Structural controls of base metal mineralization in Ireland in relation to continental drift

M. J. Russell B.Sc., Stud.I.M.M.

Report of discussion at November, 1968, general meeting (Chairman: Dr. S. H. Shaw, President) and contributed remarks. Paper published in *Transactions/Section B (Applied earth science)*, vol. 77, Aug. 1968, pp. B117–28

M. J. Russell outlined his hypothesis on the origin of base metal deposits in Ireland, which was that, as most of the large base metal deposits in Carboniferous rocks lay on a north–south straight line, that implied a vertical fissure control of the mineralization. He believed that that fissure came up from the upper mantle, and that both the genesis of the deposits and their siting resulted from fissuring. Any escaping magma or other fluid from the mantle would take advantage of weaknesses formed at the intersection of cross-faults with the fissures, thus causing hot spots in the upper crust, which would, in turn, give rise to convection in pore waters. The hot waters in that convective system would dissolve lead, zinc, copper and barium ions and precipitate them over the intersections in rocks or, in favourable conditions, on the sea-floor. Therefore he felt that the controversy between the doctrines of epigenesis and syngenesis was not significant in Ireland.

It had to be admitted that his evidence was permissive and circumstantial; nevertheless, he hoped that it was a hypothesis which might help to guide research and exploration. The mainstay of the hypothesis was the distribution of four major sulphide deposits in Carboniferous rocks along a north–south line. The second line was a speculation based on the four sandstone inliers and the mineralization at Keel. Those two hypothetical fissures were parallel to other structures on the continental margin of northwest Europe, and could not be explained, in his opinion, by a Hercynian stress field. However, the Foynes Trough drawn with a north–south axis in Fig. 1 (p. B118) on the strength of the distribution of Middle and Upper Carboniferous rocks in western Ireland was erroneous, as Dr. P. R. R. Gardiner had pointed out.*

The age of continental drift was very much in doubt at the present time. Some geologists believed that early drift began in the Devonian in the general area under discussion; but geophysicists favoured a Jurassic or Cretaceous or even early Tertiary age. He emphasized that the important time was that of first adjustments to the stress field related to continental drift, and not the age of ocean floor spreading itself. There was some evidence of faulting and mineralization in Dinantian times.

Perhaps the most important comparison to be made with Ireland in the light of that hypothesis was to be found in the work of Kutina *et al.*,† who had pointed out that Pb, Zn, ± Cu, ± Ag mineralization was related to some of the long north–northeast trending faults in Czechoslovakia. Those faults had a spacing of between 50 and 60 km, and their age, according to J. Svoboda and his co-workers‡ was about 270 m.y. The distance between the two fissures in Ireland was 50 km.

North–south fissuring and faulting could best be explained by an east–west tensile stress field (relative to the present pole.) A north–south (Hercynian) compression would cause shear faulting in directions 30° either side of north. It was his feeling that the Hercynian had tended to become a category to which all thermal and tectonic events of Upper Palaeozoic age had been ascribed. He suggested that the newly discovered sulphide deposits in Ireland were related to continental drift, although the Hercynian movements could have played a part. It was possible anyway that the two events (continental drift and the Hercynian orogeny) were interrelated.

At present the evidence did not belie the hypothesis, which offered a possible explanation of the linear distribution of ore deposits in Ireland. The lineament approach to mineral exploration had been used by prospectors for a long time. Geologists had been more careful in invoking that simplistic approach, but there was much to commend it. He thought that there might be many other ore deposits related to lineaments formed under tensile stress yet to be discovered in the world, especially in 'docile' continental margin areas.

C. J. Morrissey then summarized the comments which are presented as a written contribution on pages B48–51.

Dr. J. A. E. Allum said that Mr. Russell's fascinating hypothesis that the newly discovered base metal deposits of Ireland were controlled by the intersection of north–south upper mantle fissures with east–west to northeast–southwest faults of Caledonian trend could obviously be considered without reference to continental drift. For the hypothesis to obtain the discussion and consideration it deserved he thought it might be better if it were not associated too closely with the theory of continental drift: it could stand or fall by itself. There was always the danger that the valuable new hypothesis would be lost in the discussion of the even more valuable theory of continental drift. The time to link the origin of the fissures with continental drift was when the existence of the fissures had been proved.

At the expense of exposing his ignorance of Irish geology, he asked the following questions concerning Fig. 1 which the paper immediately inspired. The southernmost of the Castleblayney veins deposits was exactly where a prolongation of the northeast–southwest fault through the Riofinex deposit would meet the prolongation of the Kingscourt Fault; he asked if it were known for certain that the Riofinex Fault did not continue to the northeast. Secondly, if the central northeast–southwest fault south of Ferbane continued in a southwesterly direction, exactly parallel to the Tynagh Faults to the north and the Silvermines Fault to the south, it would pass through the Garrykennedy and Ballyvergin deposits; he asked if it were known for certain that that fault did not so continue. Finally, he asked whether they were to consider the north–south fault in the southeast corner of Fig. 1 as being the surface expression of a third north–south upper mantle fissure. He thought that questions such as those should have been anticipated in the paper.

Obviously, the author must have considered those questions when he prepared the map. He had referred to other related questions in the section entitled 'Economic considerations of the hypotheses' (pp. B126–7). If one assumed Mr. Russell's hypothesis of north–south upper mantle fissures, and extended the major faults in Fig. 1 in the established directions, one found immediately nine new areas to prospect. The whole matter, therefore, was one of great economic as well as scientific interest, and would justify expenditure in further work. He said the question was: 'How could they obtain more evidence concerning the existence of the postulated north–south upper mantle fissures and the possible prolongations of the northeast–southwest faults?' It was assumed that little more could be done by conventional surface geological mapping.

Remote-sensing techniques, such as aerial geophysics, photogeology and the study of sideways-looking radar photography and satellite photography, might provide the best means of investigating the existence of postulated earth fractures. One would like to be able to assume that all available information of that kind had already been considered. The author might have felt that no professional geologist would fail to use aerial photographs in a study of the present kind if they were available, and therefore a reference to them in his paper was unnecessary. The speaker assured him that that was not so, as he would have liked to have been informed whether aerial photographs or any other sources of

*Personal communication; see also page B51.

†Kutina J. Pokorny J. and Vesela M. Empirical prospecting net based on the regularity distribution of ore veins with application to the Jihlava mining district, Czechoslovakia. *Econ. Geol.*, 62, 1967, 390–405.

‡Cited by Kutina and co-workers (see reference above).

remotely sensed data were available. If they were not available, attention should be drawn to the disadvantages exploration geology suffered in those circumstances. If they were available, he would have liked to have been told how they were used and with what results.

It was known that earth fractures were often indicated on aerial photographs, even when they were invisible on the ground. He believed, therefore, that the best and least expensive approach to a problem of that kind was to study stereo pairs and photograph mosaics or print laydowns of the whole deposit area. If the results of the photogeological study were positive, but scepticism was still felt as to the reliability of that method, then supporting evidence could be sought from the more expensive and perhaps less subjective methods of geophysics, and more particularly aerial geophysics. In that way there would be little expenditure before there was a high probability of there being something worth investigating.

R. W. Laing* said that he was working on terrestrial resources and environmental sensing systems. To add to Dr. Allum's remarks about the extent and use of aerial surveys, he had within the last few days been informed by the Irish Air Corps that the only aerial photographs they had taken were of the Counties of Leigh, Wicklow and Dublin, and that they had taken no pictures whatever of locations containing the postulated fissure/fault intersections. He understood that in 1969 they hoped to have black and white stereoscopic cover of Tipperary, Donegal, Mayo and Galway.

That led him to the whole question of the dearth of remote surveying by dynamic electromagnetic means.

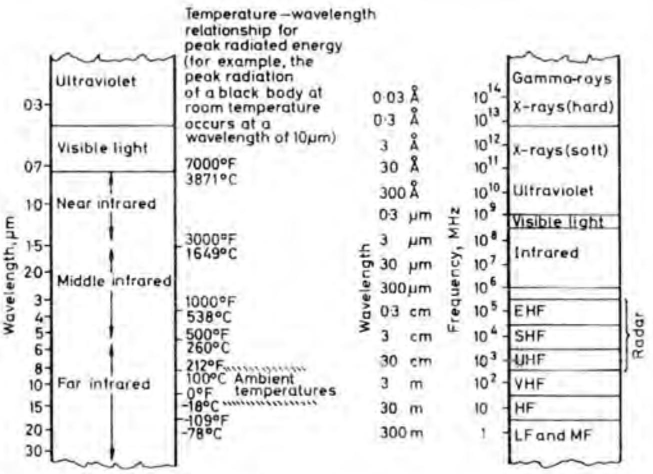

Fig. 1 The electromagnetic spectrum

Fig. 1 showed a chart of the electromagnetic spectrum; he drew attention to the restricted view they had at present with aerial photography. The left-hand side of the chart showed the small visible spectrum contained by the ultraviolet and infrared spectra. Common infrared films and plates operated only to wavelengths of about 1·2–1·3 μm, which were in the near infrared. The right-hand side of the chart showed how the spectral range on the left-hand side stood in relation to the entire spectrum.

Types of remote sensors under comparative evaluation by the United States Geological Survey, the United States National Aeronautics and Space Administration (NASA) and by a host of academic communities in America included the following: metric mapping camera; panoramic high-resolution camera; ultra-high-resolution camera; multi-band synoptic camera; ultraviolet camera; television camera; microwave imager; microwave radiometer; microwave spectrometer; radar scatterometer; radar imager; radar altimeter; infrared line scanner; infrared imager; infrared radiometer/scatterometer; infrared spectrometer; laser altimeter; and laser scatterometer.

It was interesting to note that 'infrared', used there in connexion with devices such as linescanners and radiometers, meant wavelengths at least three times, and in some cases a thousand times, larger than for normal film and plate camera infrared. Truly, a vast effort was being made in the U.S.A. to bring those new tools to work.

Tables 1 and 2 were based on a detailed tabulation produced by the United States Geological Survey of the evaluating experiments carried out continuously and systematically since 1966 with aircraft; similar programmes were being pursued for agriculture, forestry, geography, hydrology and oceanography. That organized drive grew from several earlier years of experimentation.

Great use has been made by the Americans of orbital altitude photographs from their manned space vehicles and from unmanned recoverable satellites. For the remote sensing of environment they believed that satellites equipped with ultra-high-resolution infrared linescan or multi-band imaging spectrophotometers, for example, would be of immensely greater value.

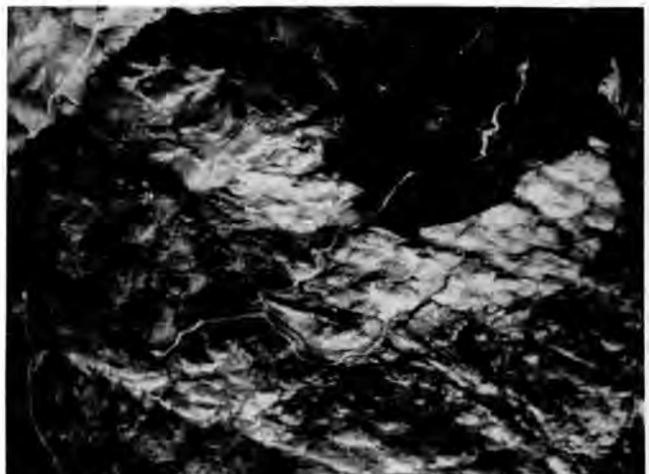

Fig. 2 Infrared linescan imagery. Contributed by permission of the Director, Royal Radar Establishment, Malvern. © Copyright the Controller, H.M.S.O.

In the United Kingdom all the skills required for that type of work existed—as did much of the hardware. Little use was at present being made of those skills for civilian purposes. Figs. 2 and 3 showed imagery (he specifically avoided the word 'photograph', as that immediately had connotations of the visible spectrum): they were of aerial views of a mountain region in Wales, and were taken at night by the use of thermal infrared linescan. They were not, of course, reflected images, but were the result of transmission of heat energy from the ground. A similar device was carried on Nimbus weather satellites and, in fact, several experimenters had done work in geology on that type of imagery from Nimbus infrared radiometers, which gave much coarser ground resolution.

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Table 1 Geologic natural resource experiments to be conducted from air and space. Compiled by U.S. Geological Survey

Title of experiment	Specific application (or geoscience problem) and parameters to be measured, interpretative features to be studied	Test sites to be utilized
Thermal region of volcanoes	Convective heat transfer of selected volcanoes	Hawaii; Philippines; Cascades (California), Oregon; Washington; Vesuvius; Etna; Iceland
Thermal properties of natural materials	Investigations in variation of surface temperature	Mono Crater, California; Pisgah Crater, California
Compositional mapping	Investigate utilization of scanning spectral radiometer and spectrometer	Indiana Dunes, Indiana; Salton Sea, California; White Sands, New Mexico
Geothermal power sources	Hot-spring thermal anomalies and variations	Salton Sea, California; Hot Springs, California; Benton, California
Global mean annual temperatures	Determine accuracy and precision of IR radiometry to determine absolute surface temperature versus conventional meteorological data	
Ultraviolet absorption and luminescence	UV reflectance of natural materials between 3000 and 4000 A°	Pisgah Crater, California; Meteor Crater, Mesquite, Arizona; Mono Crater, California
Special-purpose or instrument sites	Volcanic terrain (lunar analogue)	Pisgah Crater, California
	Lithology	Mono Crater, California
	Volcanic terrain	Little Dragoon Mountains
	Dome	Solitario, Texas; Donner Pass
	Plutonic rocks–lithology	Sonora Pass
	Dunes–composition	Devils Playground
	Impact features (lunar analogue)	Meteor Crater, Arizona
	Hydrology	Guadelupe River; Wichita Mountains
	Structure	Spanish Peaks, Colorado; Hopi Buttes, New Mexico
	Lithology	Cape Cod, Massachusetts
Structural geology	San Andreas Fault, earthquake zone structure	Stillwater/East Ranges, Nevada; Coast Ranges, Oregon
	Faults–lithology	Southern Oregon
	Earthquake	San Andreas Fault
	Thermal areas	Central Cascade Range
	Folds, major uplifts and intrusions	Baltimore (Hartford–York); Hagers Town; Battle Mountain, Nevada; Wichita Mountains; Great Sage Plain, Utah
	Structure stratigraphy	Eastern Beartooth Mountains, Wyoming; Orange, Virginia
	Engineering geology, structure	Nevada Test Site; Spanish Peaks, Colorado; Cedar City, Utah; Smoke Creek Desert, Heber, Utah; Dixie Valley, Nevada; Lynn District, Nevada; Goldfield, Nevada; Big Pine Fault, California; Mount Morrison Fault, California; Mississippi Valley

Aircraft surveys investigating 8·5–16 μm infrared had indicated how acidic and ultrabasic surfaces could be detected, and calculations showed that it would still be possible from satellites.

Fig. 4 was of the Malvern Hills by sideways-looking airborne radar (SLAR); again, he issued a caution not to regard it as a black and white photograph taken by a camera but to bear in mind that the wavelength used was of the order of ten million times greater than that normally utilized. Obviously, interpretation was not a straightforward matter, and that was duly appreciated in the U.S.A., as was shown by the extent of the programmes workers there had been involved in for so many years.

Hawker Siddeley Dynamics were at present involved with the production of infrared linescan devices, and slides were shown of such devices and of one of their 'Blue Streak' rockets lifting a payload typical of that required for an earth resource satellite fitted with such sensors.

Table 2 Geologic natural resource experiments to be conducted from air and space. Compiled by U.S. Geological Survey

Type of experiment	Specific application (or geoscience problem) and parameters to be measured, interpretative features to be studied	Test sites to be utilized
Mineral diagnosis	Fault sources; rock types (gross) alteration sources	Iron Springs, Utah; Eureka, Utah; Salt Lake district, Utah; San Francisco district, Utah; Carson City (Comstock); Silver City (central district) New Mexico; Ourey–Silverton–Creda district; Twin Buttes, Arizona; Tonapsh; Mesabi Iron Range; Gogebic Iron Range; Coal Field, Kentucky; Ironton, Maine; Blackbird district, Idaho; NE Pennsylvania; Hawaii; Alberton, Montana; Tobacco Root, Montana; Mesquite Set. Site, Arizona
Stratigraphy–sedimentation; general geologic	Lithologic composition, structure; stratigraphy; thermal springs; engineering problems, aggregate	Yellowstone National; Inyo National Forest, California; Hopkinton–Milford; Templeton Orange; Cleveland Co.; Puerto Rico; North Slope, Alaska
General geology additions	Foreign sites	Pinacata Hills, Mexico; Central Mexico; Quadrilatero, Ferrifero, Brazil; Alice Springs, Australia

Fig. 3 See caption to Fig. 2

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8. **Wobber F. J.** Put geology surveys in orbit to find oil. *Oil Gas J.*, **65**, Dec. 11 1967, 158–62.

Frank Yeates said he liked the comprehensive manner in which the author had tackled the subject of base metal mineralization in Ireland. He had approached the subject logically, by which he meant that the author had worked from the whole to the part, from the general to the particular. He had described first the geological environment of the base metals before commenting on them individually.

The paper had, however, disappointed him in its lack of any reference to the Conlig–Newtownards lead mines in Co. Down, and he would like to draw attention to comments he had made in 1958* and in 1965.† It would then be clear what it was he so much wanted to know and had made repeated efforts during the last ten years to have determined.

He had enquired into the feasibility of aerial surveys of the ground incorporating the mines to see if they threw any light, from surface indications, of the possibility of ore below the 40-fathom level in the 'unworked area', as the abandonment plan described it, or in any extension of the lode. Although the cost of such a survey was quite moderate, he had not been able to meet it personally or to obtain any financial backing.

*Yeates F. Contribution to discussion of **Fowler A.** The non-ferrous minerals of Northern Ireland. In *The future of non-ferrous mining in Great Britain and Ireland* (London: The Institution of Mining and Metallurgy, 1959). [27–34] 38–41.

†Yeates F. Contribution to discussion of **Schnellmann G. A.** Recent developments in the search for minerals in the United Kingdom. [*Trans. Instn Min. Metall.*, **74**, Aug. 1965, 673–7] *Trans. Instn Min. Metall.*, **74**, Aug. 1965, 684–8.

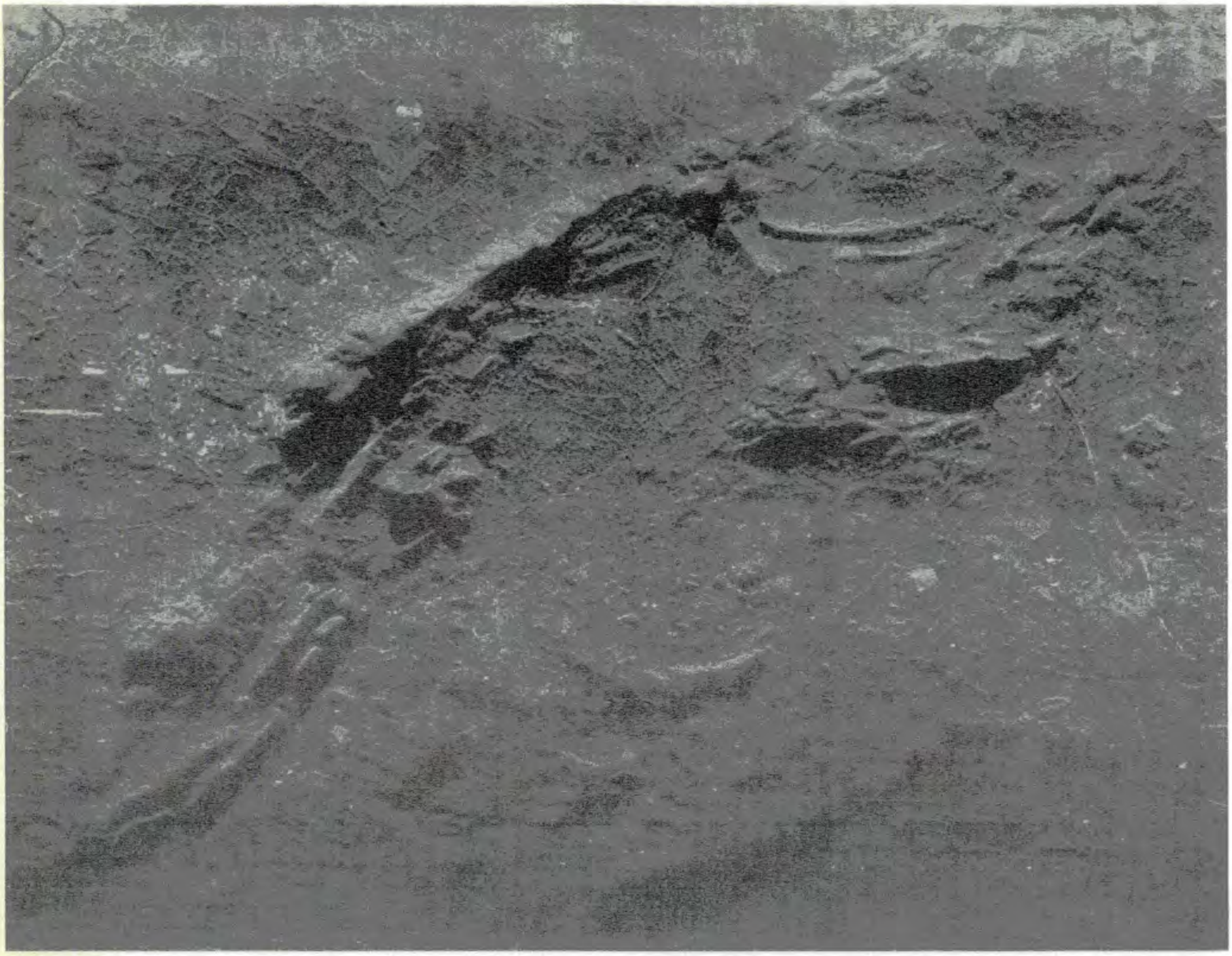


Fig. 4 Malvern Hills by SLAR. Contributed by permission of the Director, Royal Radar Establishment, Malvern.

Enquiries had also been made of the Ministry of Commerce in Belfast. An aeromagnetic survey had, apparently, been completed, but the map had still to be published.

He looked forward to reading what the author thought, in the light of his studies, of the prospect of finding ore in the unworked ground below the 40-fathom level.

Noel Gillatt said that Mr. Russell's theory of genesis of the Irish Carboniferous deposits postulated (pp. B123–4) 'approximately north–south fissures . . . they extend from the upper mantle . . . intersected east–west to northeast–southwest faults . . . Magma rose along these fractures . . . acted as "hot spots" giving rise to a convective or partial convective system within pore waters in the Lower Palaeozoic geosynclinal rocks . . . Water, containing base metals dissolved from clay particles, organic matter and fine authigenic sulphide . . . rose along the fracture intersections and . . . the east–west faults. . . . Thus . . . the resultant ores occur . . . close to . . . the intersections'.

First, the many north–south features in Ireland were of various ages, e.g. faults were Mesozoic in age, dykes were Tertiary, and none of the Carboniferous sedimentation features was north–south—the features were demonstrated to be east–west or northeast–southwest reactivated Caledonian structures.

Mr. Russell also said (p. B122) that 'Smaller sulphide deposits in eastern Ireland also exhibit a north–south distribution'. Having quoted one locality in support of that statement in no way approached the statistical rigour required. There were numerous base metal mineral localities which did not fit Mr. Russell's conclusions and which were not considered.

Secondly, the occurrence of magmatic rocks in the Irish Carboniferous suggested that any features reaching to the lower crust or upper mantle would have controlled the location of those rocks; but, in fact, few of the known Carboniferous volcanics, other than tuffs, which manifestly might be transported, lay on Mr. Russell's postulated north–south fissure lines. Those igneous rocks lay along a northeast–southwest line. The Carboniferous magmatic centres had not acted as 'hot spots' for partial convective systems.

Thirdly, other than showing the possible adequacy of the amounts of metals available in Lower Palaeozoic geosynclinal sediments, which did not apply to Abbeytown, where the author admitted the absence of those rocks, no direct evidence of the source of either the metals or the sulphur was supplied.

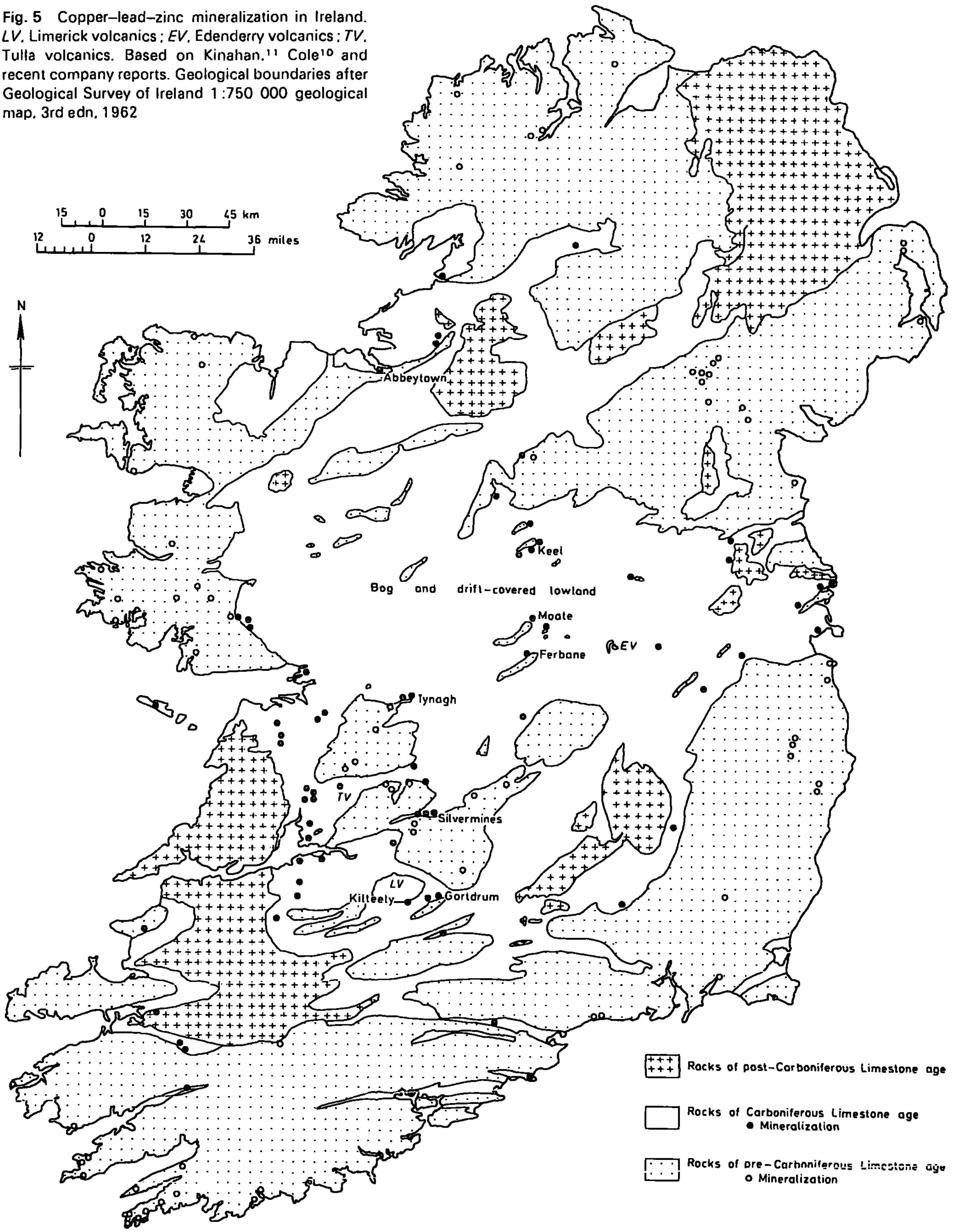
The author summarily dismissed a magmatic source by saying (p. B123): 'The absence of fluorite . . . puts a magmatic hydrothermal source theory . . . in some doubt'. That might apply to granitic magmas, but not to the intermediate-type volcanics of the Irish Carboniferous.

Mr. Russell did not consider Carboniferous connate water at all, even as a possible source of sulphur—a widely recognized occurrence in carbonate sequences.

Contributed remarks

C. J. Morrissey, J. M. Patterson, G. M. Steed and C. J. Wheatley Mr. Russell has carried out an interesting philosophical exercise, and we wish to congratulate him on his thought-provoking paper. His is the sort of hypothesis that could take a good deal of the guesswork out of exploration, but such hypotheses stand or fall

Fig. 5 Copper–lead–zinc mineralization in Ireland. *LV*, Limerick volcanics; *EV*, Edenderry volcanics; *TV*, Tulla volcanics. Based on Kinahan,[11] Cole[10] and recent company reports. Geological boundaries after Geological Survey of Ireland 1:750 000 geological map, 3rd edn, 1962



according to the quality and relevance of the information on which they are built. The recent mineral discoveries in Ireland offer an extraordinarily good opportunity of resolving some fundamental problems of ore genesis, and it is noteworthy that, with the active encouragement of industry, all the major ones are currently being investigated by research students at universities. Individually, these studies can be of considerable value to the property concerned; collectively, they will help to provide a soundly based rationale for region-wide exploration.

It may be a year or two before the results of current research programmes are published; we would therefore like to take this opportunity to comment on some of Mr. Russell's statements about the deposits that are being studied in the Mining Geology Department, Royal School of Mines, London. These include Tynagh, Gortdrum, Keel (Riofinex) and Avoca.

Mr. Russell envisages a genetic connexion between mineralization and Lower Carboniferous volcanicity, and gives the impression that Upper Palaeozoic volcanic rocks are commonly found in mineralized areas. No such rocks are known at Keel, and none were found by Rhoden[1] at Silvermines. The pyroclastic affinities of the Shallee White Shale—a green argillite with arenaceous phases in the Upper Devonian succession at Silvermines—are entirely conjectural. At Tynagh, thin graded beds of recognizable tuff with a maximum combined thickness of about 5 ft are a minor component of early Viséan sediments.[2] The grain size and composition of the material are such that it might have been windborne from the Limerick volcanic area, which is situated about 45 miles to the south of Tynagh and centred some 10 miles to the west of Mr. Russell's Abbeytown–Gortdrum line. Incidentally, the Edenderry centre of Viséan volcanicity (Fig. 5) does not fall on the same north–south line as any known mineralization in Upper Palaeozoic rocks, and it lies about midway between Mr. Russell's Riofinex–Ferbane line and the next hypothetical line to the east. Another centre of Lower Carboniferous volcanicity may be present near Tulla, Co. Clare,[3] which is 20 miles to the west of Mr. Russell's Abbeytown–Gortdrum line. Most of the known centres of Devonian volcancity are not near any of these lines.

Movement on the major ENE–WSW fault along which the Tynagh mineralization occurs may have taken place during Lower Carboniferous sedimentation, though Schultz[4] has produced evidence to the contrary. Its main movement post-dated lithification of the youngest rocks preserved in the area, which are of Lower Viséan (probably C_2S_1) age. This is also true of major fractures with approximately the same trend at Keel. At Gortdrum the Viséan and Upper Tournaisian have been removed by erosion, so it can only be said that movement on the main ENE–WSW fault took place after the *Z* stage of the Tournaisian. When the ENE–WSW faults were initiated in each case is very hard to say, but they are generally considered to be of Permo–Carboniferous (Armorican) age. There is growing evidence that Mesozoic and/or Tertiary earth movements may have caused substantial reactivation of Caledonian and Armorican structures in Ireland.[5,6]

Mineralization at Tynagh, Keel and Gortdrum occurred during or after the faulting referred to above. Rhoden reached the same conclusion about mineralization along the Silvermines Fault known in 1958. Mr. Russell's assertion that banded and colloform textures in sulphides indicate that the sulphides were deposited during sedimentation or early diagenesis is certainly not true of the Tynagh mineralization, and such textures are largely absent from sulphides at Keel and Gortdrum. The spread of the lead isotope ages of galenas from a number of localities in the Lower Carboniferous of Ireland, including Tynagh and Abbeytown, is such that the lead may have been separated from its U/Th bearing source region at any time between the early Carboniferous and the early Permian.[7,8]

Only at Keel has the temperature of sulphide deposition been established according to reliable criteria, so to say that the sulphide suites at the main mines are of low-temperature formation is premature and may not be correct. Fluid inclusion studies by Dr. E. Roedder of two specimens of sphalerite from Keel indicate that the material concerned crystallized at about 175°C. Needless to say, this figure may not be the maximum for the Keel mineralization as a whole. Some of the Tynagh mineralization may have crystallized at temperatures well above 200°C, and the same may be true of some of the mineralization at Silvermines.

At Keel faults trending approximately north–south post-date the ENE–WSW faults referred to previously. They are of comparatively minor effect. The north–south jointing at Tynagh and Gortdrum (where faults with this trend are rare or absent) is also younger than the mineralization. In the Silvermines district ENE–WSW gravity faulting was accompanied by subsidiary fracturing in two directions, one of which was north–south.[1]

There is a general lack of evidence that major north–south fractures of Upper Palaeozoic age are present in the part of Ireland which contains most of the mineral deposits mentioned by Mr. Russell. Major faults may be concealed under the widespread cover of drift and bog, but those which can be inferred in the unexposed Carboniferous limestones of the region from geophysical evidence have the Caledonoid trend of the underlying Lower Palaeozoic rocks.[9] Mesozoic and/or Tertiary earth movements were responsible for most of the north–south faulting in Ulster, and though the Kingscourt Fault may have been active and influenced sedimentation in pre-Mesozoic times, there are geophysical indications that it does not persist far to the south as a north–south structure. No other structures with this trend have demonstrably influenced Palaeozoic sedimentation, whereas sedimentation in the Silurian, Upper Carboniferous and Mesozoic was clearly influenced by structures with a Caledonoid trend.

If the deposits which fall on Mr. Russell's north–south lines are not situated at or near the intersections of two sets of fractures, what is the cause of their alignment? A point that should be made about this is that the deposits concerned are large-scale examples of a type of mineralization that occurs very widely in Ireland (Fig. 5). It should be noted that the central lowland, which is floored by rocks of the type that contain most of the main mineral deposits, is extensively covered by bog and glacial drift. Over large areas superficial deposits up to 200 ft thick reduce outcrop density to less than 0·5 per cent, and good bedrock exposures are only found in inliers of pre-Carboniferous rocks. No distinction has been drawn in Fig. 5 between styles of mineralization, since experience has shown that vein-type mineralization in one Lower Carboniferous rock type may pass down into disseminated or massive mineralization of far greater extent in another.

Whether or not the aligned deposits are a biased sample, mineralization has certainly been concentrated on the faulted margins of pre-Carboniferous inliers. This can be explained without recourse to a north–south structural control, for the main deposits may occur where structures with a Caledonoid trend in Lower Palaeozoic rocks have produced a particular type of deformation in superincumbent strata. Both the Silurian and the Devonian seas transgressed a terrain which apparently had fairly rugged relief in places, and this may partly have taken the form of ranges of hills with a Caledonoid trend. It is possible that the marked elongation of pre-Carboniferous inliers in central Ireland is to some extent a reflection of this relief, and that particularly favourable sites for mineralization were produced by Armorican reactivation of the buried structures. Present evidence suggests that highly saline solutions carrying metals leached from Lower and Upper Palaeozoic rocks moved upwards into these sites, but not that magmatic activity in the upper crust at a number of widely separated centres provided the energy for these movements.

The paramount importance of structures orientated approximately ENE–WSW in localizing mineralization is apparent at most of the major mines. Mineralization extends for at least 6 miles along the southern margin of the Keel inlier, but the north–south extent of the mineralized zone is generally less than 1500 ft. At Tynagh mineralization has been proved for more than 10 000 ft along the main fault, but its northward extent is usually less than one-twentieth of that figure. The main Tynagh orebody occurs where an ENE–WSW fault has thrown competent Devonian sandstones against a thick development of brittle Waulsortian limestones, with the formation of a zone of fracturing and brecciation in the latter which acted as a structural trap for mineralizing fluids.

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Dr. P. R. R. Gardiner* In view of the convincing way in which Mr. Russell has outlined the presence of north–south fissures, it is unfortunate that the axis of the Foynes trough has been used as supporting evidence. This does not trend north–south. Hodson and Lewarne† have demonstrated that the trough, which was initiated in the mid-Carboniferous, had an east–west orientation.

However, a further indication regarding the presence of major north–south fissures is shown by the Irish Sea earthquake of 1951. The isoseismal lines for this revealed a linear feature trending north–south, off the southeast Irish coast.‡

I agree that major structures with this alignment could be caused by continental drift, but palaeogeographic evidence and the present location of the mid-Atlantic ridge seem to favour a northwest–southeast tensional system rather than an east–west one. Has Mr. Russell considered the possibility that the two major structural directions, namely the 'Caledonoid' aligned faults and the north–south fissures, could be synchronous components of a major conjugate fault set resulting from such a tensional system? There is evidence that both north–south (e.g. the Kingscourt Fault) and east–west faults (e.g. the Tynagh and Silvermines Faults) were active in the Carboniferous. Furthermore, such an interpretation would enable the structural setting of the Irish base metal deposits to be matched more closely with those of the Red Sea area, as Armorican deformation patterns need not be invoked.

Dr. J. W. Norman If there is any validity in Mr. Russell's north–south lines they should be used as a basis of field-testing and developing suitable techniques so that eventually similar features can be detected in other parts of the world. The other intersecting directions appear more amenable to conventional mapping.

Dr. Allum has suggested some approaches which I also would like to see tested. Photogeophysics (or fracture trace analysis) would be a cheap technique in areas of existing suitable photography. Several papers have demonstrated that a pattern in young deposits can show settlement over deeper features, and it is not inconceivable that there are detectable adjustments to a deep movement that would show thus in the Carboniferous rocks and in the glacial soils. Infrared colour film is undergoing comparative tests at the Royal School of Mines, London. It appears to have given good results in detecting major fractures in a prospecting programme in a glaciated basement terrain in Finland.[1] In this case it was used as small-scale high-altitude photography. Mosaics from existing panchromatic photography can sometimes show long structures measurable in terms of miles which do not appear to be reflected in surface mapping.[2]

Mr. Laing lifted up the corner of NASA's 'Pandora's Box' for us. I am delighted that some of these devices appear to be becoming available on this side of the Atlantic. So far we have had a daunting stream of papers replete with claims for the performance of these instruments, but with surprisingly little evidence that they can show as much information as established forms of 'sensing'. This is causing experienced photogeologists to express scepticism in public[3] and in private. This is a pity as some have interesting possibilities, which systematic testing and the development of interpretation techniques in normal geological environments could establish. For example, radiometry in the far infrared part of the spectrum can be used to sense thermal emission. By the use of a mirror/imagery system instead of lenses which absorb heat it should be possible to sense from aircraft a temperature anomaly above a shallow oxidizing sulphide deposit. This heat anomaly will, however, be very small in relation to the fluctuating background and a lot of work will have to be done to establish survey and interpretation techniques to cope with this. Radar also may have possibilities beyond the overcoming of the Irish weather, for it appears to have more penetration than photography. Although its longer wavelengths probably reduces the resolution too much for some types of photogeology, it might possibly show something of Mr. Russell's north–south features.

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M. V. OBrien Satisfactory explanation of deep-seated causes of geological phenomena must generally be sought from scattered evidence and long lines of inference which show the greatest probability of being correct. Ordinarily, it is impossible to prove or disprove such an explanation but only to raise or lower its probability of correctness above or below the point at which it has some usefulness either academically or commercially.

For base metal occurrences in the Lower Carboniferous of Ireland, the commercial and economic importance of good working hypotheses of control of their location, size, kind and content are extremely desirable to guide the expensive prospecting methods necessarily employed through the drift-covered plains. The continuance, 7 years after the Tynagh discovery and after the further discoveries at Gortdrum, Silvermines, Keel and elsewhere, of persisting programmes by a dozen separate companies or company groups implies a widely held opinion that hypotheses on localization of such occurrences have hitherto been useful only to an incomplete degree.

A new hypothesis could be better than its predecessors and, therefore, important, even at a relatively low level of probability. Rebuttal or questioning of some of Mr. Russell's evidence or inferences may lower the probable validity of his hypothesis, but not necessarily below the point at which it has a utility. Some at least of the overlap with earlier discussion has been eliminated to shorten the following comments.

North–south trend does not automatically mean parallelism with the continental margin. The margin cited, west of the Porcupine Bank, is arcuate through 60 degrees from N20W to N40E. It is 300 miles away. The nearest part of the continental shelf (judged from bathymetry) is 200 miles away off the northwest coast of Ireland and trends southwest–northeast.

Real and relevant north–south trends may be significantly less numerous than Mr. Russell suggests. Much predominant north–south jointing seems adequately accounted for by the Armorican pressures which produced east–west folds. Such joints and north–south Devonian dykes would seem to have a relevance only if it were shown that they were distinctly more frequent in north–south zones some 30 miles apart, the frequency apparently postulated for the deep-seated 'fissures'. The north–south gravity anomalies of the Irish west coast are of no real help in considering this matter until F. Gray and A. P. Stacey put their findings on record to supplement their personal communication to Mr. Russell.

*Geological Survey of Ireland, Dublin.

†Hodson F. and Lewarne G. C. A mid-Carboniferous (Namurian) basin in parts of the counties of Limerick and Clare, Ireland. *Q. Jl geol. Soc. Lond.*, 117, 1961, 307–33.

‡Ingram R. E. Cited by Nevill W. E. *Geology and Ireland* (Dublin: Allen Figgis, 1963), p. 165.

Mr. Russell records no independent geological evidence of a north–south fissure through or near Keel.

In Fig. 1 the north–south line through Keel (Riofinex) is extended for 100 miles. Only the central 35 miles of that has a supporting argument in the text, where reference is made to its passage past the ends of four gently dipping and plunging anticlines; the plan position of their ends may be quite susceptible to local erosion levels.

Mr. Russell's main argument for his hypothesis seems to lie in his statement (p. B123) that the 'continuity of these fissures suggests they extend from the upper mantle'. This seems to need strengthening as he is, in effect, relying only on two lines, one real but the other lacking independent significance, and neither in fact related by geological or geophysical evidence to fissures.

The principal supporting evidence appears to be in Mr. Russell's reference (p. B124) to 'Similar fractures parallel to the continental margin . . . present in the Maritime Provinces of Canada' and 'Replacement deposits . . . found in association with these fractures'. No research or references are cited to establish the evidence and arguments for the connexion of these Canadian mineral occurrences with fracture lines associated with continental drift.

Certain subsidiary points mentioned by Mr. Russell may not be essential to his main argument, but they appear to put on record as statements of accepted fact aspects of Irish economic geology which do not appear to be correct. (*a*) The reference (p. B117) to Tynagh, Silvermines, Gortdrum and Keel as showing 'similarities with the strata-bound deposit at Abbeytown' may suggest that all are strata-bound. About one-half the output of Abbeytown came from one stratigraphical horizon (where a difference of competence may have made the beds particularly vulnerable to fracturing) and one-half from irregular bodies over the 150 ft of strata below. Published sections of Tynagh, Silvermines and Gortdrum show extensive mineralization at and across various horizons spreading over stratigraphical ranges of, respectively, at least 600 ft, 450 ft and 300 ft. (*b*) The statement (p. B118) that in 'the south of Ireland the Upper Old Red Sandstone is often enriched in chalcopyrite and bornite' needs to be substantiated or, at least, to be clarified in that a very large proportion of the copper minerals are in extremely close association with quartz veins which can cut many hundreds of feet of vertical extent of these sandstones. (*c*) The silver contents quoted (p. B121) appear from older papers to be the silver contents per ton of lead and not per ton of ore.

Regional geochemical reconnaissance in Sierra Leone

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Authors' reply to discussion* on paper published in *Transactions/ Section B* (*Applied earth science*), vol. 75, May, 1966, pp. B147–61

Dr. Ian Nichol, Dr. L. D. James and Dr. K. A. Viewing We are grateful to the contributors for their comments and for the interesting and important questions which they asked.

The objective of the research programme was to investigate the value of multi-element geochemical drainage reconnaissance as a source of information in mineral exploration and fundamental geology in conditions operating in Sierra Leone. The success of a geochemical survey as a whole is dependent on the selection of appropriate sampling and analytical techniques and an adequate interpretation of the data. To a considerable extent the methods employed in any programme frequently represent a compromise between those which are technically desirable and those which are acceptable on the basis of time and cost.

As was stated in the paper, in general terms the sampling procedure adopted was based on the results of a detailed study of metal dispersion in soils, stream sediments and waters associated with Mo and As–Au mineralization, carried out previously by colleagues in the Applied Geochemistry Research Group at Imperial College, London.[1–3] The sampling and analytical procedures employed in the reconnaissance with reference to As–Au and Mo were those recommended by Elliott,[2] who found that the −80-mesh fraction of the stream sediment gave the longest anomalous dispersion trains. The stream water in barren and mineralized areas contains very small quantities of As and Mo, and the contrast between the waters draining mineralization and background areas is small. On this basis, together with the fact that water sampling presents problems of transport due to instability, the reconnaissance sampling was restricted to the collection of stream sediments.

The sample density was between four and five samples per square mile. The target was set, initially, at one sample per square mile, previous experience of the Applied Geochemistry Research Group having indicated that this density could be expected to reveal geochemical patterns of significance on a regional scale. Experience in the field area indicated that the sample density could be increased to four samples per square mile, without reducing the area which was to be covered, within the time available. It is evident from the geochemical maps (Figs. 4 and 5, p. B150), however, that most of the significant geochemical patterns would have been revealed by a density of two samples per square mile.

The sample sites were selected by using air photographs in combination with the excellent series of geological maps, scale 1 : 50 000, which cover the area. Access to the sample sites is seldom easy in Sierra Leone, for the tropical rain forest and the secondary growth is so dense that it is difficult to penetrate. The maximum use was made of paths which connect the villages and the outlying farms, but where no paths exist the stream beds were the only means of access. Mr. R. Phillips (pp. B70–1) mentioned the variable density of the sampling indicated by Fig. 9 (p. B159). An important aspect of the research was to determine the characteristic geochemical parameters of specific rock types, and nine type areas were selected for detailed sampling. It is fortuitous that the lower illustration in Fig. 9 includes an area in which five of the streams drain small catchments underlain by basic and ultrabasic rocks, and these streams were sampled at relatively close intervals in order to obtain a series of representative samples.

**Trans. Instn Min. Metall.* (*Sect. B: Appl. earth sci.*), 76, Feb. 1967, B69–72.